OPERATING INSTRUCTIONS

for

TYPE 874-LB SLOTTED LINE

GENERAL RADIO COMPANY

CAMBRIDGE 39 MASSACHUSETTS

NEW YORK CHICAGO LOS ANGELES

U. S. A.

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OPERATING INSTRUCTIONS

for

TYPE 874-LB SLOTTED LINE

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CAMBRIDGE 39 MASSACHUSETTS

NEW YORK CHICAGO LOS ANGELES

U. S. A.

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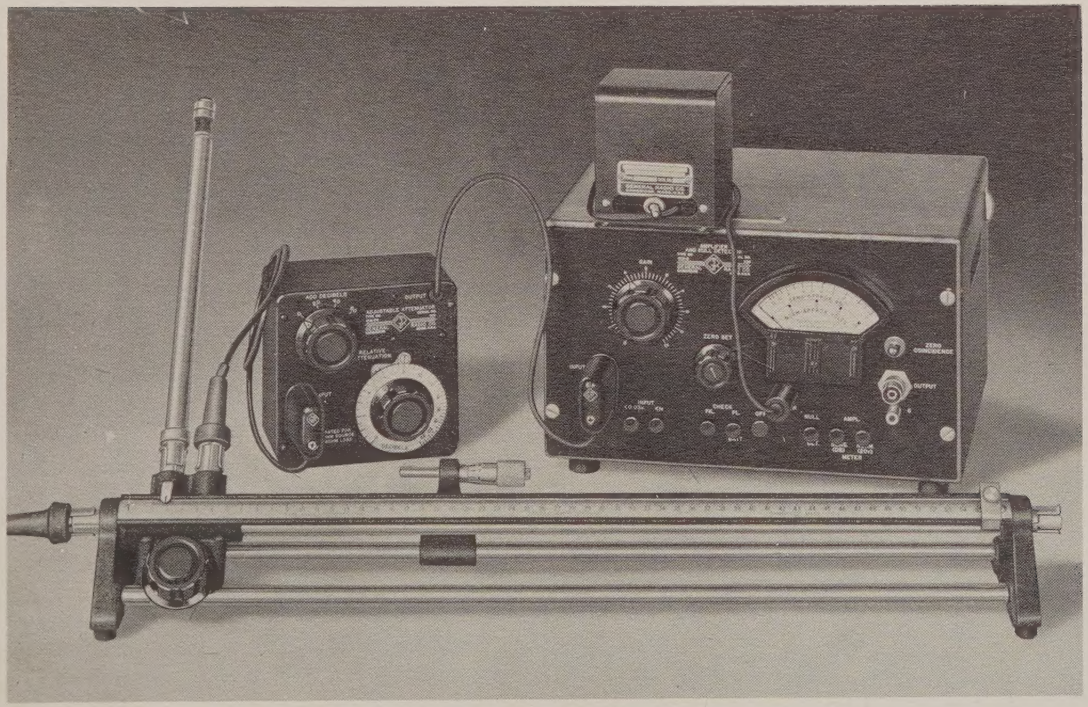

View of equipment for standing-wave and impedance measurements. Shown with the Type 874-LB Slotted Line are the following accessories: Type 874-D20 Adjustable Stub, Type 874-LV Micrometer Vernier, Type 1231-P4 Adjustable Attenuator, Type 1231-B Amplifier with Type 1231-P2 Tuned Circuit, and Type 874-R32 Patch Cord.

OPERATING INSTRUCTIONS

for

TYPE 874-LB SLOTTED LINE

Section 1.0 General Description

One of the important basic measuring instruments used at ultra-high frequencies is the slotted line. With it, the standing-wave pattern of the electric field in a coaxial transmission line having a known characteristic impedance can be accurately determined. From a knowledge of the standing-wave pattern several characteristics of the circuit connected to the load end of the slotted line can be obtained. For instance, the degree of mismatch between the load and the transmission line can be calculated from the ratio of the amplitude of the maximum of the wave to the amplitude of the minimum of the wave, which is called the voltage standing-wave ratio, VSWR. The load impedance can be calculated from the standing-wave ratio and the position of a minimum point on the line with respect to the load. The wavelength of the exciting wave can be measured by obtaining the distance between minima, preferably with a lossless load to obtain the greatest resolution, as successive minima or maxima are spaced by one-half wavelengths. The properties outlined above make the slotted line valuable for many different types of measurements on antennas, components, coaxial elements, and networks.

The Type 874-LB Slotted Line is designed to measure the standing-wave pattern on a coaxial transmission line having a 50-ohm characteristic impedance over a frequency range from about 300 to 5000 Mc. A small probe mounted on a sliding carriage extends through a slot into the region between the inner and outer conductors of a coaxial line and samples the electric field in the line. The probe is connected to a detector, and the variation in electric field intensity, and hence the voltage along the line, can be determined by sliding the carriage along the line while noting the output of the detector.

Section 2.0 Theory

2.1 CHARACTERISTIC IMPEDANCE AND VELOCITY OF PROPAGATION

A transmission line has uniformly distributed inductance and capacitance, as shown in Figure 1. The series resistance due to conductor losses and shunt resistance due to dielectric losses are also uniformly distributed, but will be

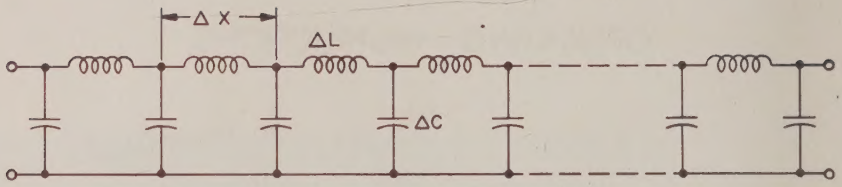

Figure 1. Circuit showing the distribution of inductance and capacitance along a transmission line.

neglected for the present. The square root of the ratio of the inductance per unit length, L, to the capacitance per unit length, C, is defined as the characteristic impedance, Z_0, of the line.[1]

$$Z_0 = \sqrt{\frac{L}{C}} \tag{1}$$

In the next paragraph, transmission-line behavior will be discussed in terms of electromagnetic waves traveling along the line. The waves travel with a velocity, v, which depends on L and C in the following manner:

$$v = \frac{1}{\sqrt{LC}} \tag{2}$$

If the dielectric used in the line is air and the permeability is unity, the product of L and C for any uniform line is always the same and results in a velocity equal to the velocity of light, c, (3×10^{10} cm/sec). If the dielectric has an effective dielectric constant, K, greater than unity, the velocity of propagation will be lower than the velocity of light by the square root of the effective dielectric constant.

$$v = \frac{c}{\sqrt{K}} \tag{3}$$

The relationship between frequency, f, and wavelength, λ, in the transmission line is

$$\lambda f = v \tag{4a}$$

$$f = \frac{v}{\lambda} \tag{4b}$$

$$\lambda = \frac{v}{f} \tag{4c}$$

[1] As indicated in footnote 2, this is an approximation which is valid if line losses are low. The approximation gives satisfactory results for most practical applications at high frequencies.

If the dielectric is air and the permeability is unity,

$$\lambda f = 3 \times 10^{10} \quad \text{cm./sec.} \qquad (4d)$$

if λ is in centimeters and f is in cycles per second.

2.2 TRAVELING AND STANDING WAVES

The performance of a transmission line having a uniform characteristic impedance can be explained using a wave approach in which an electromagnetic wave is considered which travels along the line from the generator to the load where all or a portion of it may be reflected with or without a change in phase, as shown in Figure 2a. The reflected wave travels in the opposite direction along the line back toward the generator. The phases of these waves are retarded linearly 360° for each wavelength traveled.

The wave traveling from the generator is called the incident wave, and the wave traveling toward the generator is called the reflected wave. The combination of these two traveling waves produces a stationary interference pattern on the line which is called a standing wave, as shown in Figure 2b. The maximum amplitude of the standing wave occurs when the incident and reflected waves are in phase, or an integer multiple of 360° out of phase. The minimum amplitude occurs when the two waves are 180°, or an odd integer multiple thereof, out of phase. The amplitude of the standing wave at other points along the line is the vector sum of incident and reflected waves at each other point. Successive minima and maxima are spaced, respectively, a half-wavelength along the line, as shown in the figure.

The magnitude and phase of the reflected wave at the load relative to the incident wave are functions of the load impedance. For instance, if the load impedance is the same as the characteristic impedance of the transmission line, the incident wave is totally absorbed in the load and there is no reflected wave. On the other hand, if the load is lossless, the incident wave is always completely reflected with no change in amplitude but with a change in phase.

A traveling electromagnetic wave actually consists of two component waves, a voltage wave and a current wave. The ratio of the magnitude and phase of the incident voltage wave, E_i, to the magnitude and phase of the incident current wave, I_i, is always equal to the characteristic impedance, Z_o. The reflected waves travel in the opposite direction from the incident waves, and consequently the ratio of the reflected voltage wave, E_r, to the reflected current wave, I_r, is $-Z_o$. Since the characteristic impedance in most cases is practi-

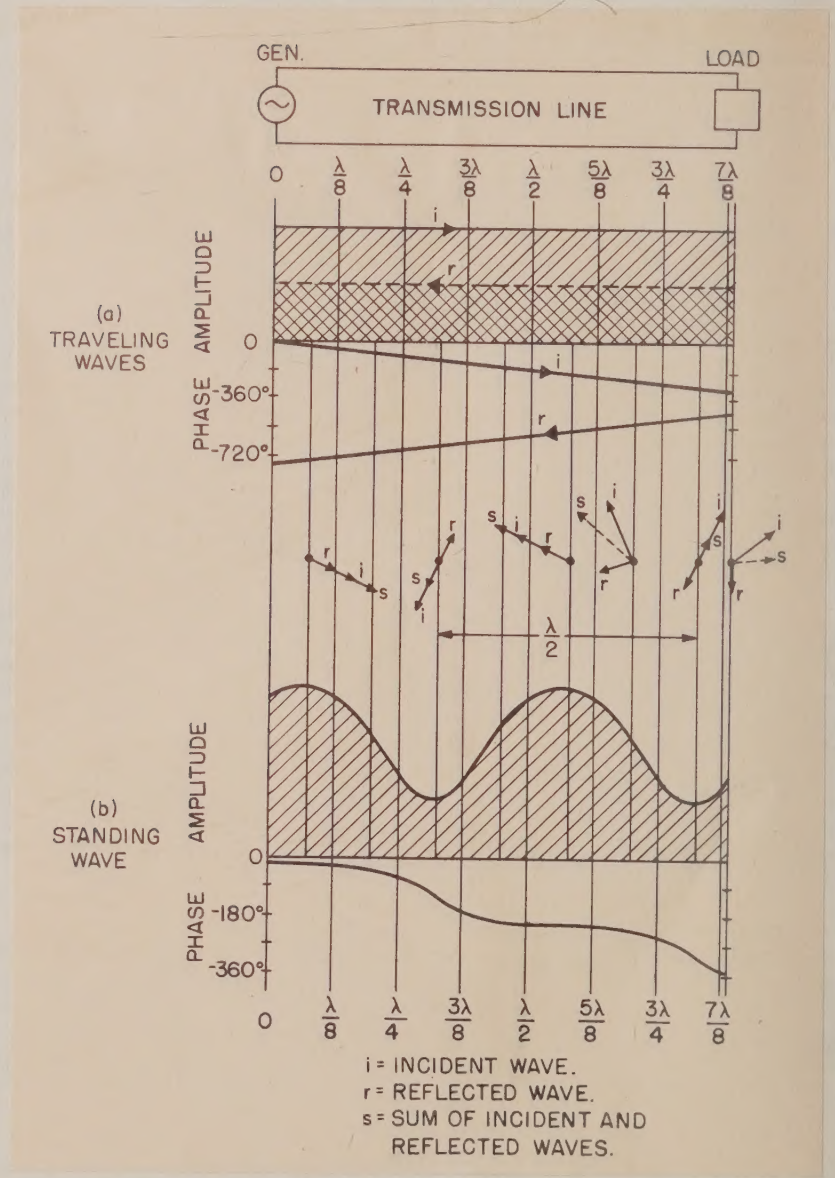

Figure 2. (a) Chart showing the variations in the amplitude and phase of incident and reflected waves along a transmission line. (b) The vector combination of the incident and reflected waves at various points along the line is illustrated and the resultant standing wave produced by the combination of the two waves is plotted.

cally a pure resistance,[2] the incident voltage and current waves are in phase with each other and the reflected voltage and current waves are 180° out of phase.

$$\frac{E_i}{I_i} = Z_o \qquad (5a)$$

$$\frac{E_r}{I_r} = -Z_o \qquad (5b)$$

Equations (5a) and (5b) are valid at all points along the line.

The magnitude and phase of the reflected voltage wave, E_r, relative to incident wave, E_i, at the load is called the reflection coefficient, Γ, which can be calculated from the expression

$$\Gamma = \frac{Z_x - Z_o}{Z_x + Z_o} = \frac{Y_o - Y_x}{Y_o + Y_x} \qquad (6)$$

$$E_r = E_i \Gamma \quad \text{at the load} \qquad (7a)$$

$$I_r = -I_i \Gamma \quad \text{at the load} \qquad (7b)$$

where Z_x and Y_x are the complex load impedance and admittance, and Z_o and Y_o are the characteristic impedance and admittance of the line. ($Y_o = \frac{1}{Z_o}$).

2.3 LINE IMPEDANCE

If the line is terminated in an impedance equal to the characteristic impedance of the line, there will be no reflected wave, and $\Gamma = 0$, as indicated by Equation (6). The voltage and current distributions along the line for this case are shown in Figure 3.

If the line is open-circuited at the load, the voltage wave will be completely reflected and will undergo no phase shift on reflection, as indicated by

---

2

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = \sqrt{\frac{L}{C} \times \frac{1 - j\frac{R}{\omega L}}{1 - j\frac{G}{\omega C}}} \simeq \sqrt{\frac{L}{C}}$$

where L is the inductance per unit length in henries, C is the capacitance per unit length in farads, R is the series resistance per unit length in ohms, and G is the shunt conductance per unit length in mhos. The approximation is valid when the line losses are low, or when $\frac{R}{L} = \frac{G}{C}$.

Equation (6), ($Z_X = \infty$), while the current wave will also be completely reflected but will undergo a 180° phase shift on reflection, as shown in Figure 4. If the line is short-circuited, the current and voltage roles are interchanged and the impedance pattern is shifted $\lambda/4$ along the line. The phase shifts of the voltage and current waves on reflection always differ by 180° as the reflected wave travels in the opposite direction from the incident wave. A current maximum, therefore, always occurs at a voltage minimum, and vice versa.

The voltage at a maximum of the standing-wave pattern is $|E_i| + |E_r|$ or $|E_i|(1 + |\Gamma|)$ and at a minimum is $|E_i| - |E_r|$ or $|E_i| \times (1 - |\Gamma|)$. The ratio of the maximum to minimum voltages, which is called the voltage standing-wave ratio, VSWR, is

$$\text{VSWR} = \frac{E_{max}}{E_{min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \qquad (8a)$$

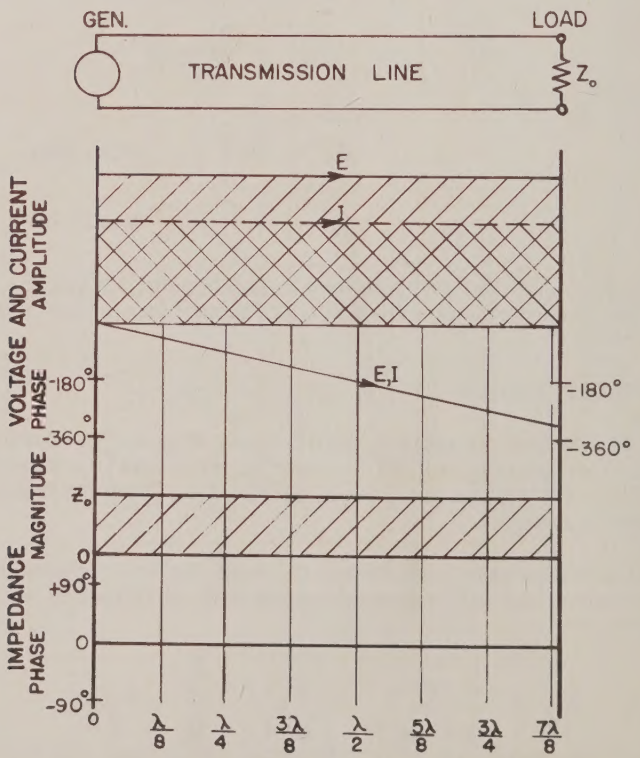

Figure 3. Chart showing voltage and current waves along a transmission line terminated in its characteristic impedance. Note the absence of reflected waves and that the impedance is constant and equal to the characteristic impedance at all points along the line.

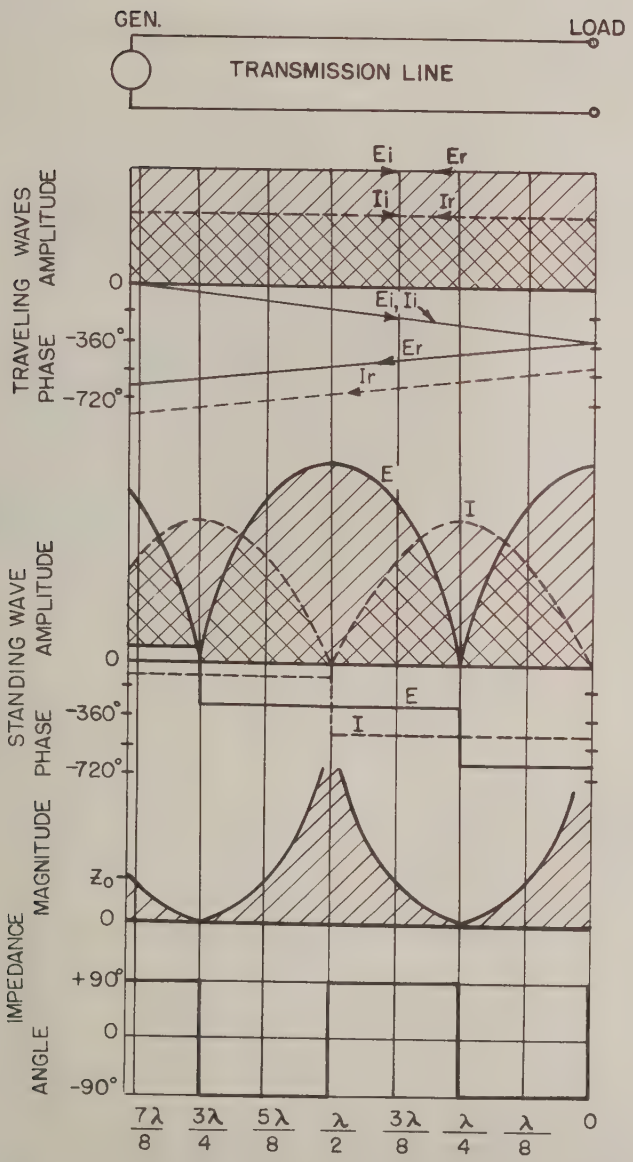

Figure 4. Chart showing voltage and current waves along a transmission line terminated in an open-circuit. Note that the minima of the voltage waves occur at the maxima of the current waves, and vice versa, and that the separation of adjacent minima for each wave is a half-wavelength. The variation in the magnitude and phase angle of the impedance is also shown.

The standing-wave ratio is frequently expressed in decibels, in which case it is referred to as SWR.

$$SWR = 20 \log_{10} \frac{E_{max}}{E_{min}} \qquad (8b)$$

The impedance, Z_p, seen looking towards the load at various points along a uniform lossless line, is the ratio of the magnitude and phase of the effective voltage at the point in question to that of the effective current at the same point and varies along the line in a cyclical manner, repeating each half-wavelength of the line, as shown in Figure 4.

At a voltage maximum on the line, the incident and reflected voltage waves are in phase, and the incident and reflected current waves are 180° out of phase with each other. Since the incident voltage and incident current waves are always in phase (assuming Z_0 is a pure resistance), the effective voltage and current at that point are in phase, and the effective impedance at that point is pure resistance. At a voltage minimum, the two voltage waves are opposing and the two current waves aiding, and again the effective impedance is a pure resistance. At a voltage minimum, the resistance is equal to the characteristic impedance of the line divided by the VSWR, and, at a voltage maximum, it is equal to the characteristic impedance multiplied by the VSWR.

$$R_{p\,max} = Z_0 \times (VSWR) \qquad (9a)$$

$$R_{p\,min} = \frac{Z_0}{VSWR} \qquad (9b)$$

The impedance, Z_p, at any point along the line is related to the load impedance by the expression

$$Z_p = Z_0 \times \frac{Z_x + jZ_0 \tan\theta}{Z_0 + jZ_x \tan\theta} \qquad (10a)$$

$$Y_p = Y_0 \times \frac{Y_x + jY_0 \tan\theta}{Y_0 + jY_x \tan\theta} \qquad (10b)$$

where Z_x and Y_x are the complex load impedance and admittance, Z_0 and Y_0 are the characteristic impedance and admittance of the line, and θ is the electrical length of line between the load and the point along the line at which the impedance is measured. (See Figure 5.)[3] The effective length, ℓ_e, is proportional to the physical length, ℓ, multiplied by the square root of the effective

[3] In Figure 5, point 'p' is shown at a voltage minimum. However, Equations (10a) and (10b) are valid for any location of point 'p' on the line.

dielectric constant, K, of the insulating material between the inner and outer conductors.

$$\ell_e = \ell\sqrt{K} \tag{11a}$$

$$\theta = \frac{\ell_e}{\lambda} \text{ wavelengths} \tag{11b}$$

$$\theta = \frac{2\pi\ell}{\lambda}\sqrt{K} \text{ radians} \tag{11c}$$

$$\theta = \frac{360\ell}{\lambda}\sqrt{K} \text{ degrees} \tag{11d}$$

If ℓ is in centimeters,

$$\theta = 0.012 f_{mc} \ell\sqrt{K} \text{ degrees} \tag{11e}$$

2.31 Determination of the Load Impedance from the Impedance at Another Point on the Line: The load impedance, Z_x, or admittance, Y_x, can be determined if the impedance, Z_p, at any point along a lossless line is known. The expressions relating the impedances are:

$$Z_x = Z_o \times \frac{Z_p - jZ_o \tan\theta}{Z_o - jZ_p \tan\theta} \tag{12a}$$

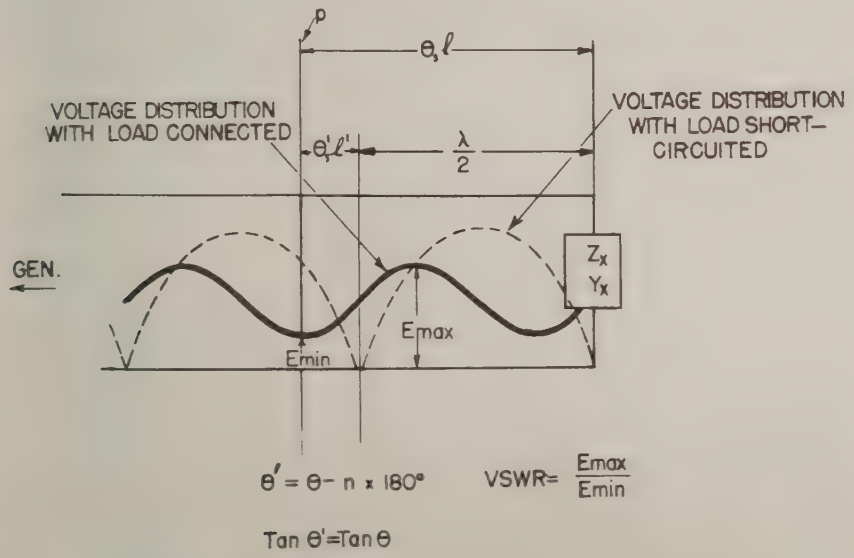

Figure 5. Voltage variation along a transmission line with a load connected and with the line short-circuited at the load.

$$Y_x = Y_o \times \frac{Y_p - jY_o \tan\theta}{Y_o - jY_p \tan\theta} \qquad (12b)$$

If the line loss cannot be neglected, the equations are:

$$Z_x = Z_o \times \frac{Z_p - Z_o \tanh\gamma\ell}{Z_o - Z_p \tanh\gamma\ell} \qquad (13a)$$

$$Y_x = Y_o \times \frac{Y_p - Y_o \tanh\gamma\ell}{Y_o - Y_p \tanh\gamma\ell} \qquad (13b)$$

where $\gamma = \alpha + j\beta$, and

α = attenuation constant in nepers/cm. = $\frac{\text{att. in db/100 ft.}}{26490}$

β = phase constant in radians/cm. = $2\pi f\sqrt{LC} = \frac{2\pi\sqrt{K}}{\lambda}$

2.32 Determination of the Load Impedance from the Standing-Wave Pattern: The load impedance can be calculated from a knowledge of the VSWR present on the line and the position of a voltage minimum with respect to the load, since the impedance at a voltage minimum is related to the VSWR as indicated by Equation (9b). Equation (9b) can be combined with Equation (12a) to obtain an expression for the load impedance in terms of the VSWR and the electrical distance, θ, between the voltage minimum and the load.

$$Z_x = Z_o \times \frac{1 - j(\text{VSWR})\tan\theta}{\text{VSWR} - j\tan\theta} \qquad (14a)$$

$$= Z_o \times \frac{2(\text{VSWR}) - j\left[(\text{VSWR})^2 - 1\right]\sin 2\theta}{\left[(\text{VSWR})^2 + 1\right] + \left[(\text{VSWR})^2 - 1\right]\cos 2\theta} \qquad (14b)$$

Since in a lossless line the impedance is the same at half-wavelength intervals along the line, θ can be the electrical distance between a voltage minimum and any multiple of a half-wavelength from the load (see Figure 5). Of course, if the half-wavelength point used is on the generator side of the voltage minimum located with the load connected, θ will be negative. The points corresponding to half-wavelength distances from the load can be determined by short-circuiting the line at the load and noting the positions of the voltage minima on the line. The voltage minima will occur at multiples of a half-wavelength from the load.

If the VSWR is greater than 10 and $\frac{\tan\theta}{VSWR} < 0.1$, the following approximation of Equation (14b) gives good results.

$$R_x \cong \frac{Z_o}{VSWR\cos^2\theta} \qquad (15a)$$

$$X_x \cong -Z_o\tan\theta \qquad (15b)$$

2.33 Smith Chart: The calculation of the impedance transformation produced by a length of transmission line using the equations previously presented can be time consuming. Mr. P. H. Smith[4] has devised a chart, shown in Figure 6, which simplifies these calculations. In this chart the circles whose centers lie on the resistance component axis correspond to constant values of resistance and the arcs of circles whose centers lie on an axis perpendicular to the resistance axis correspond to constant values of reactance. The chart covers all values of impedance from zero to infinity and the position of a point corresponding to any given complex impedance can be found from the intersection of the resistance and reactance coordinates corresponding to the resistive and reactive components of the unknown impedance.

The impedance seen looking along the line toward a fixed unknown will travel around a circle with its center at the center of the chart as the distance from the load is increased or decreased. The angular movement around the circle is proportional to the electrical displacement along the line. One complete traverse of the circle will be made for each half-wavelength of travel. The radius of the circle is a function of the VSWR.

2.331 Calculation of Impedance at One Point from the Impedance at Another Point on a Line: If the impedance at one point on a line, say at a point "p," is known, and the impedance at another point a known electrical distance away (for instance, at the load) is desired, the problem can be solved using the Smith Chart in the following manner. First, locate the point on the chart corresponding to the known impedance, as shown in Figure 6. (For example, assume that $Z_p = 20 + j25$ ohms.) Then, draw a line from the center of the chart through Z_p to the outside edge of the chart. If the point at which the impedance is desired is on the load side of the point at which the impedance is known, travel along the WAVELENGTHS TOWARD LOAD scale, from the intersection of the line previously drawn, a distance equal to the electrical distance in wavelengths between the point at which the impedance is known and the point at which it is desired. If the point at which the impedance is desired is on the generator side of the point at which the impedance is known, use the WAVELENGTHS TOWARD GENERATOR scale. (In this example, assume that the electrical distance is 0.11 wavelength toward the load.) Next, draw a circle through Z_p with its center at the center of the chart, or lay out, on the last radial line drawn, a dis-

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[4] Smith, P.H., Electronics, Vol. 17, No. 1, pp. 130-133, 318-325, January 1944.

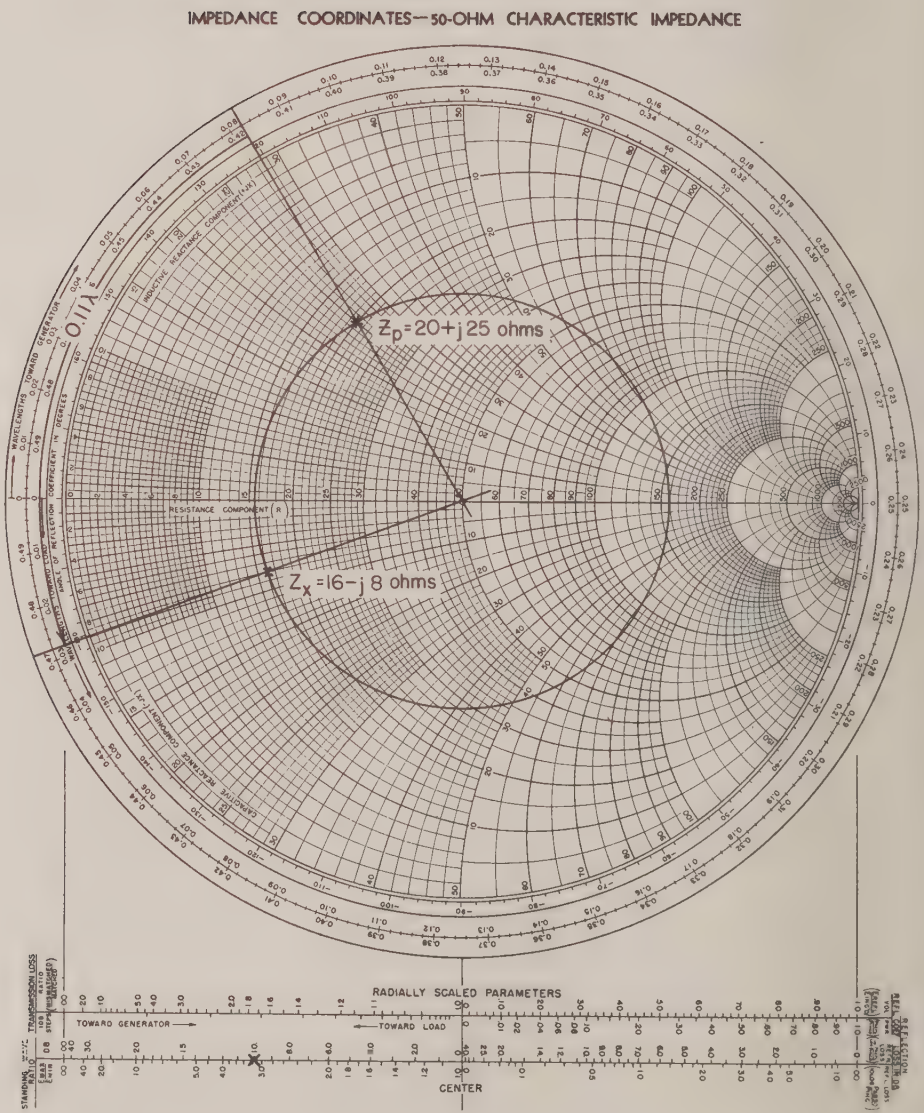

Figure 6. Illustration of the use of the Smith Chart for determining the impedance at a certain point along a line when the impedance a specified electrical distance away is known. In the example plotted, the known impedance, Z_p, is 20 + j25 ohms and the impedance, Z_x, is desired at a point 0.11 wavelength toward the load from the point at which the impedance is known.

tance equal to the distance between Z_p and the center of the chart. The coordinates of the point found are the resistive and reactive components of the desired impedance. (In the example chosen, the impedance is 16 - j8 ohms.)

The VSWR on the line is a function of the distance which the point, corresponding to the impedance, is from the center of the chart. To find the VSWR, lay out the distance on the STANDING WAVE RATIO scale located at the bottom of the chart, and read the VSWR as a ratio, $\frac{E_{max}}{E_{min}}$, or SWR in db off the appropriate scale. (In the example, the VSWR is 3.2 or the SWR is 10.1 db.)

2.332 Calculation of Impedance at the Load from the VSWR and Position of a Voltage Minimum: In impedance measurements in which the voltage standing-wave pattern is measured, the impedance at a voltage minimum is a pure resistance having a magnitude of $\frac{Z_o}{VSWR}$. This point can be plotted on the resistance component axis and a circle having its center at the center of the chart drawn through the point. The impedance at any point along the transmission line must lie on this circle. The load impedance can be determined by traveling around the circle from the original point an angular distance indicated on the WAVELENGTHS TOWARD LOAD scale equal to the electrical distance, expressed as a fraction of a wavelength, between the voltage minimum and the load (or a point a half-wavelength away from the load, as explained in Paragraph 2.32.) If the half-wave point chosen lies on the generator side of the minimum found with the load connected, travel around the chart in the opposite direction, using the WAVELENGTHS TOWARD GENERATOR scale. The radius of the circle can be determined directly from the VSWR expressed as a ratio or the SWR in decibels, if desired, using the scales labeled STANDING WAVE RATIO located at the bottom of the chart.

The example plotted on the chart in Figure 7 shows the procedure for determining the load impedance when the VSWR is 5 to 1, and the electrical distance between the load or a half-wavelength point and a voltage minimum is 0.14 wavelength. The unknown impedance read from the chart is 23 - j55 ohms.

The Smith Chart can also be used when the line between the load and the measuring point is not lossless. The procedure for correcting for loss is outlined in Paragraph 4.61.

NOTE: Additional copies of the Smith Chart, drawn for a 50-ohm system in either impedance or admittance coordinates, are available. The Impedance Chart, similar to the one shown in Figure 6 but printed on transparent paper, is Form 756-Z, and the Admittance Chart, similar to Figure 8, is Form 756-Y.

2.333 Conversion from Impedance to Admittance: The transformation between impedance and admittance can be easily made using the chart by advancing around the circle of constant VSWR exactly 0.25 wavelength from the impedance point and multiplying the coordinates of the point obtained by 0.4 to obtain the conductance and susceptance in millimhos, as illustrated in Figure 7. This conversion property is a result of the inversion of impedance every

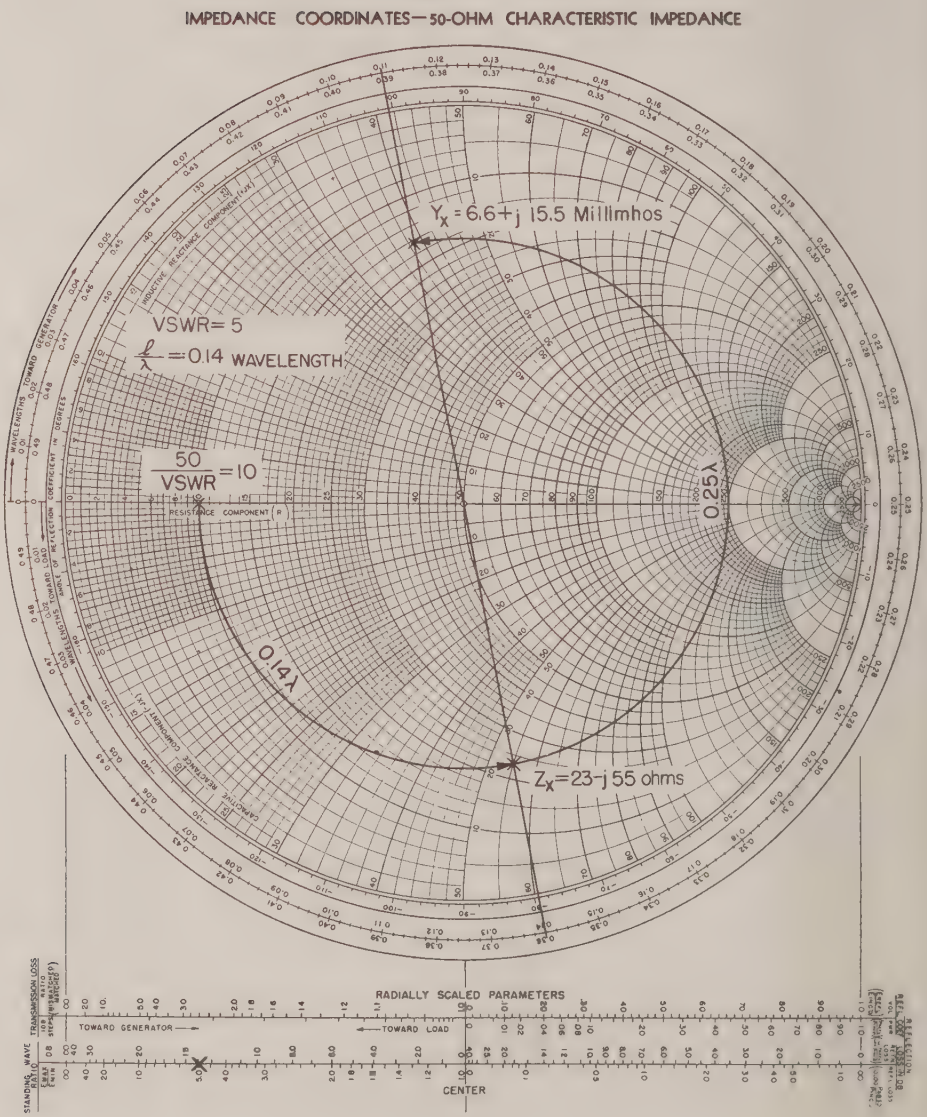

Figure 7. Example of the calculation of the unknown impedance from measurements of the VSWR and position of a voltage minimum, using a Smith Chart. The measured VSWR is 5 and the voltage minimum with the unknown connected is 0.14 wavelength from the effective position of the unknown. A method of determining the admittance of the unknown is also illustrated.

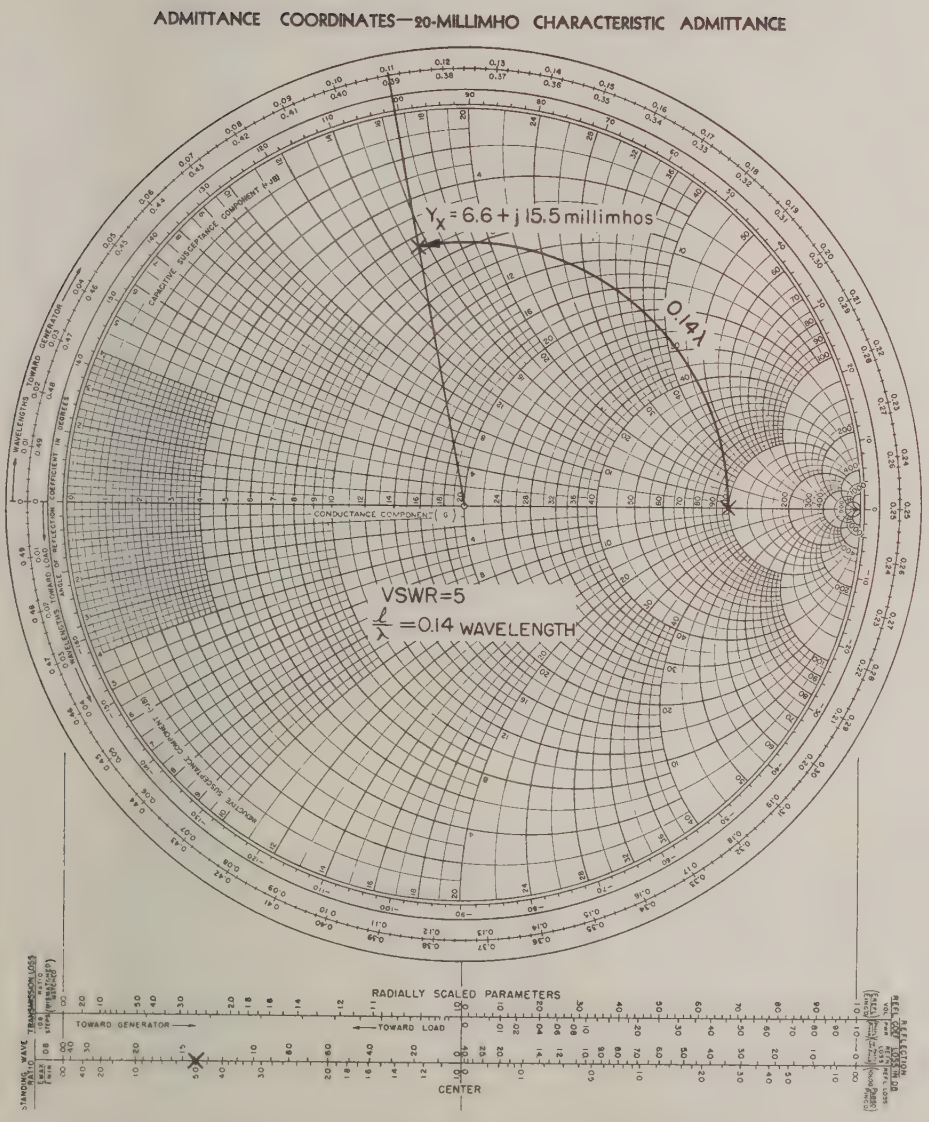

Figure 8. Example of the calculation of the unknown admittance from measurements of the VSWR and the position of a voltage minimum, using the Smith Chart drawn for admittance measurements on lines having characteristic admittances of 20 millimhos (50 ohms).

quarter-wavelength along a uniform transmission line. The impedances at points a quarter-wavelength apart are related by the equation

$$Z_1 = \frac{Z_0^2}{Z_2} \qquad (16a)$$

or

$$Z_1 = Z_0^2 Y_2 \qquad (16b)$$

2.334 Admittance Measurements Using the Smith Chart: The admittance of the unknown can be obtained directly using a normalized Smith Chart, or the chart shown in Figure 8, whose coordinates are admittance components, rather than by the procedure outlined in Paragraph 2.333. When the chart shown in Figure 8 is used, the characteristic admittance, 20 millimhos, is multiplied by the measured VSWR to find the conductance at the voltage minimum and the radius of the corresponding admittance circle on the chart found by plotting the measured conductance directly on the conductance axis. The radius can also be found from the STANDING WAVE RATIO scale located at the bottom of the chart. The electrical distance to the load is found and laid off on the WAVELENGTHS TOWARD LOAD scale, starting at 0.25 wavelength. The coordinates of the point on the VSWR circle corresponding to the angle found on the WAVELENGTHS scale are the conductance and susceptance of the unknown.

The example plotted on the chart is the same as that used for the impedance example of Figure 7.

2.335 Use of Other Forms of the Smith Chart: In some forms of the Smith Chart, all components are normalized with respect to the characteristic impedance to make the chart more adaptable to all values of characteristic impedance lines. If normalized charts are used, the resistance component value used for the voltage minimum resistance is $\frac{1}{\text{VSWR}}$, and the unknown impedance coordinates obtained must be multiplied by the characteristic impedance of the line to obtain the unknown impedance in ohms and, if the admittance is desired, the coordinates corresponding to the admittance should be multiplied by the characteristic admittance.

The normalized Smith Chart is produced in a slide rule form by the Emeloid Corporation, Hillside, New Jersey.

Section 3.0 Description

3.1 SLOTTED LINE DESIGN

The Type 874-LB Slotted Line is designed to measure the voltage standing-wave pattern along a coaxial transmission line having a 50-ohm characteristic impedance. The outer conductor is slotted for a length of approximately 50 centimeters, and a small shielded probe extends into the region between the two conductors. The probe is mounted on a carriage which slides along the outside of the outer conductor. The capacitive coupling between the probe and the line can be adjusted over a wide range by varying the penetration of the probe into the inner line. This is accomplished by screwing the probe in or out. Cross-sectional views of the probe arrangement are shown in Figure 9.

Since the probe is capacitively coupled to the line, the voltage induced in the probe circuit is proportional to the voltage existing between the inner and outer conductors of the line at the probe position.

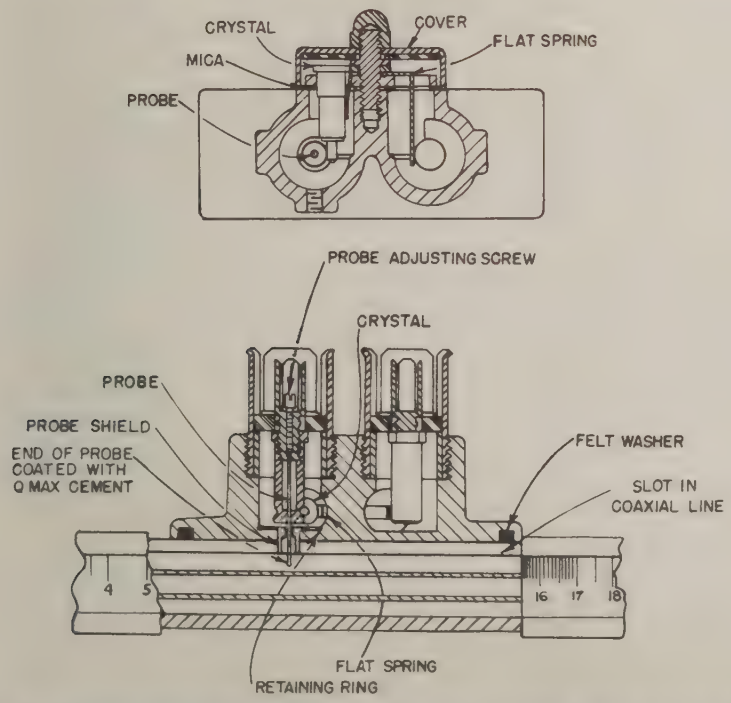

Figure 9. Cross-sectional views of the carriage on the Type 874-LB Slotted Line, showing the crystal mount and the adjustable probe.

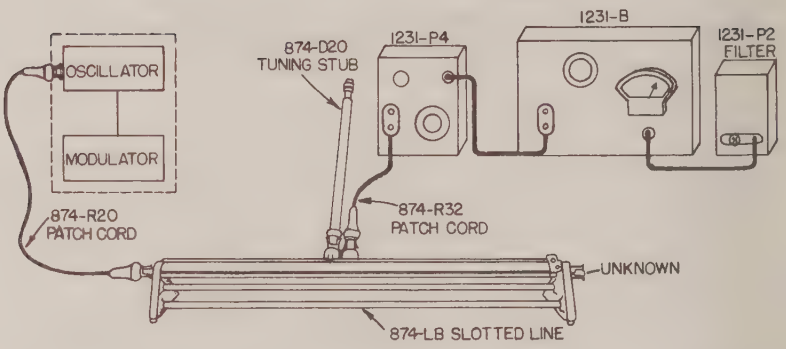

Figure 10. A typical setup for measurements with the Type 874-LB Slotted Line, using a modulated source. The built-in crystal detector and an external tuned audio amplifier are used to detect the voltage induced in the probe. The probe is tuned by means of the tuning stub shown.

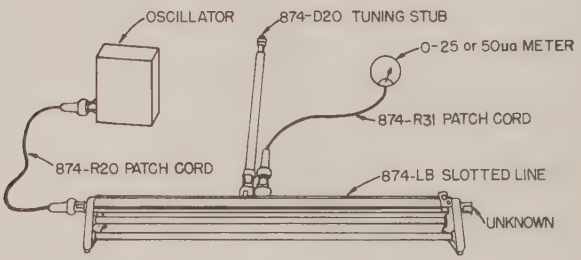

Figure 11. A typical setup for measurements with the Type 874-LB Slotted Line using an unmodulated source and a microammeter as the indicator.

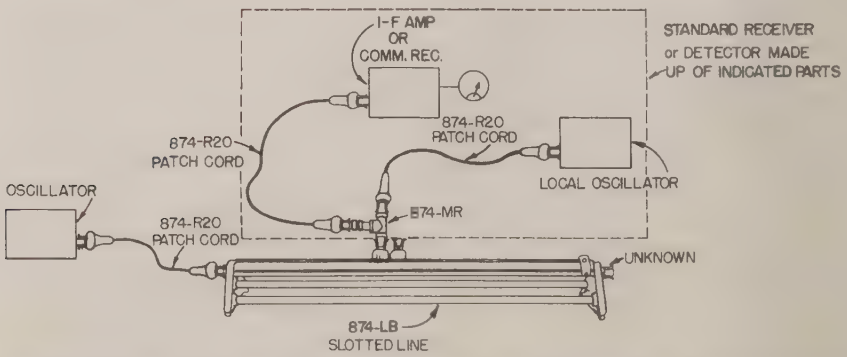

Figure 12. A typical setup for measurements with the Type 874-LB Slotted Line using an unmodulated source and a superheterodyne detector or receiver.

The r-f voltage induced in the probe can be measured by means of a built-in tuned crystal detector and associated indicating equipment as shown in Figures 10 and 11, or by means of an external receiver as shown in Figure 12.

One end of the slotted line is terminated in the circuit under test, usually called the unknown, and the other in the power source. Each end is fitted with a Type 874 Connector which introduces only a very small reflected wave in the line at frequencies up to about 7000 Mc.

3.2 GENERATOR

The generator requirements are dependent on the type of detector used and the standing-wave ratio of the load to be measured. Table I is a chart showing several possible combinations of generators and detectors along with advantages and disadvantages of the arrangements. Besides the generators indicated in the table, the Type 1208-A Oscillator can be used from 65 to 500 Mc and the Type 857-A Oscillator from 100 to 500 Mc, although the shielding of the latter is relatively poor and in some cases may cause difficulty.

3.3 DETECTOR

As mentioned previously, either the built-in crystal detector[5] or an external receiver may be used as a detector.

3.31 Crystal Rectifier and Audio Amplifier: The most commonly used detector consists of the built-in crystal rectifier with an external audio amplifier and attenuator as shown in Figure 10. In this case, of course, the oscillator driving the line must be modulated, and for best results, the audio amplifier should be tuned to the modulation frequency. The Type 1231-B Amplifier with the Type 1231-P2 Tuned Circuit and the Type 1231-P4 Attenuator is well suited for this application.

At very low levels, the crystal operates in the so-called square-law region, that is, the rectified output is proportional to the square of the r-f input. At high levels the crystal approaches a linear characteristic. In most cases, the crystal is operated in the square-law range. When the Type 1231-B Amplifier and associated filter and attenuator are used, the square-law region[6] with typical crystals extends to r-f inputs with 50% modulation, which produce full-scale deflection of the meter on the amplifier with the amplifier gain set at maximum and the Type 1231-P4 Attenuator set at 30 db. At inputs less than this value, the deviation from the square-law characteristic is less than 1/2 db.

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[5] If desired, Type 610-A Bolometer elements, manufactured by Polytechnic Research and Development Co., can be inserted in place of the crystal.

[6] The actual response of a crystal can be determined by applying known amounts of r-f power to the slotted line from a signal generator or an oscillator equipped with an accurately calibrated attenuator such as the Type 874-GA Adjustable Attenuator, or by measuring the standing-wave pattern with the line open-circuited and determining the deviation from the theoretical half-sine-wave characteristic.

Table I Detector Characteristics

DETECTOR	OSCILLATOR SIGNAL	EQUIPMENT	ADVANTAGES	DISADVANTAGES
Crystal (Built in)	Modulated (Type 1209-A U-H-F Oscillator and Type 1214 Modulator, or Type 1021-AU U-H-F Signal Generator can be used from 250 to 920 Mc.)	Audio amplifier* with indicating meter (Type 1231-B Amplifier with Type 1231-P2 Filter and preferably Type 1231-P4 Calibrated Attenuator).	1. Good sensitivity if audio amplifier gain adequate. 2. Simple. 3. Well shielded. Leakage in measurement of high SWR's rarely a problem. 4. Performance when used with Type 874-F500 and Type 874-F1000 Low-Pass Filters satisfactory for most measurements. 5. Covers a very wide frequency range.	1. Harmonic rejection poor. May cause trouble in measurement of high SWR's. Can be cured by low-pass filter. 2. If sine-wave modulation is used, frequency modulation usually produced at upper end of oscillator frequency range may cause trouble in measurement of very high SWR's. Square-wave modulation eliminates difficulty.
Crystal (Built in)	CW (Type 1209-A U-H-F Oscillator or Type 1021-AU U-H-F Signal Generator can be used from 250 to 920 Mc.)	Microammeter with sensitivity of 50 μa or better.	1. Simple. 2. Covers a very wide frequency range.	1. Insensitive, requires large oscillator power. Oscillators referred to do not have adequate output even for moderately high SWR measurements.
Receiver (Type 874-MR Mixer Rectifier)	CW (Type 1209-A U-H-F Oscillator or Type 1021-AU U-H-F Signal Generator can be used from 250 to 920 Mc.)	Type 874-MR Mixer Rectifier,** Type 1208-A or 1209-A Oscillator and either a Type 1216-A I-F Amplifier, a communications receiver, or the i-f amplifier section of an AN/APR4 or an AN/APR1 receiver.	1. Good sensitivity. 2. Very well shielded against leakage. 3. Covers a wide frequency range. 4. Good selectivity.	1. Requires several pieces of equipment. However, much of this is usually available in the laboratory.
Receiver (Such as AN/APR4, AN/APR1, etc.)	CW (Type 1209-A U-H-F Oscillator or Type 1021-AU U-H-F Signal Generator can be used from 250 to 920 Mc.)	Receiver.	1. Good sensitivity. 2. Good selectivity.	1. Some receivers are not sufficiently well shielded for use at very high frequencies.

* Thurston, W.R. "Simple Complete Coaxial Measuring Equipment for the U-H-F-Range," General Radio Experimenter, Vol. 24, No. 8, January 1950.

** Karplus, E., "Type 874-MR Mixer Rectifier," General Radio Experimenter, Vol. 24, No. 12, May 1950.

For most accurate results, the ratio of the outputs obtained at a maximum and at a minimum on the line should be measured on the Type 1231-P4 Attenuator, rather than on the meter scale, by measuring the difference in attenuation required to produce the same meter reading for a voltage minimum as for a voltage maximum. If the crystal is operating in the square-law region, the actual db difference in r-f voltage is half the db difference measured by the attenuator or meter.

3.32 Crystal Rectifier and Microammeter: An even simpler detector system consists of the built-in crystal rectifier used with an external microammeter, as shown in Figure 11. In this case, the rectified d-c output of the crystal is measured by connecting a sensitive microammeter between the inner and outer terminals of the right-hand connector on the probe carriage. In most cases, the rectified d-c output is closely proportional to the square of the r-f input at currents up to roughly 50 microamperes. The limit of the square-law region is greatly affected by the resistance of the microammeter since the r-f crystal impedance varies with the d-c bias voltage developed across the meter, and, therefore, for the most accurate results, the law of the detector should be checked at the operating frequency using an r-f attenuator.

The sensitivity of this system is poor, and difficulties are usually encountered in measuring even moderately high VSWR's unless the oscillator output is large, as the probe coupling required may be excessive (see Paragraph 4.3). The simplicity of the system makes it attractive in many cases when low VSWR's are to be measured.

The detector can be used beyond its square-law range by calibrating it, using an r-f attenuator to control accurately the relative input to the line, or actually to adjust the r-f input at the voltage maximum and at the voltage minimum to produce the same meter indication. In the second method, the VSWR can be read from the r-f attenuator and all dependence on the detector response eliminated.

3.33 The Type 874-MR Mixer Rectifier as a Detector: The combination of the Type 874-MR Mixer Rectifier, a local oscillator or signal generator such as a Type 1208-A or 1209-A Unit Oscillator, and a communications-type receiver or i-f amplifier strip, such as the Type 1216-A I-F Amplifier, shown in Figure 12, comprises an excellent detector, particularly for measuring circuits with high VSWR's, as the sensitivity and harmonic rejection are very good (see Paragraph 4.63). The communications receiver used should have a bandwidth of at least 20 kc to minimize difficulties arising from small drifts of the r-f oscillators. Bandwidths of the order of a megacycle or so, such as are obtained using high-frequency amplifiers, are very desirable for this application. The shielding of this detector is excellent, a property which is useful when measuring radiating systems. Harmonics of the local oscillator frequency can be used to beat with the signal from the slotted line and, hence, the upper frequency limit may be several times the upper frequency limit of the oscillator.

In order to measure VSWR accurately, the output meter, or S meter, on the receiver must be accurately calibrated for relative input, or the receiver

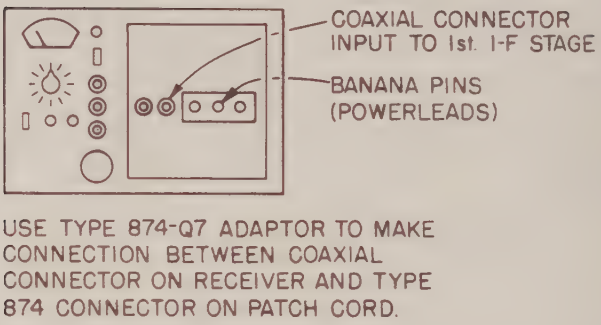


Figure 13. Method of connecting the 30-Mc output of a Type 874-MR Mixer Rectifier to the i-f amplifier in an AN/APR-1 or AN/APR-4 Receiver. The receiver tuning unit is removed for this application.

output measured. The calibration of the S meter can be checked using a low-frequency signal generator. The indicating meter on an APR-1 or APR-4 i-f Amplifier (complete receiver without tuning units) used with the Type 874-MR Mixer Rectifier provides a much better measurement means, as the indication is closely directly proportional to the i-f input voltage at indications above 1/4 of full scale. The i-f gain control can be calibrated to measure VSWR's too large to be directly measurable on the meter. The step switch on the APR-4 unit is better suited to accurate calibration than the continuously variable control found on the APR-1. The shielding of the combination of the mixer rectifier and the i-f section of the receiver is much superior to that of either the APR-1 or APR-4 used with their regular tuning units. The method of making the connection to the i-f amplifier in these receivers is indicated in Figure 13.

The mixer-rectifier output-vs-input variation is closely linear for signal input voltages up to about 50 mv when the rectified d-c crystal current produced by the local oscillator alone is at least 200 μa. The rectified crystal current can be checked by disconnecting the i-f amplifier and connecting a milliammeter between the inner and outer conductors. To prevent damage to the crystal, the current should not exceed 10 milliamperes.

3.34 High-Frequency Receiver as a Detector: Various high-frequency receivers such as the AN/APR-1 and AN/APR-4 Radar Search Receivers can be used as highly selective detectors and have the advantages for high VSWR measurements mentioned in Paragraph 4.63. The operation is similar to that obtained using the Type 874-MR Mixer Rectifier with the i-f amplifier of one of these receivers, as described in the previous paragraph, with the exception that the shielding is much poorer, particularly at the higher frequencies, and difficulties with leakage are frequently encountered, particularly when measuring radiating systems. The sensitivity obtained, however, may be slightly greater than that obtained using the mixer rectifier.

Section 4.0 Operation

4.1 CONNECTIONS AND ADJUSTMENTS

In use, the slotted line is fed from an oscillator which is connected to one end of the line, and the circuit to be measured is connected to the other end. If a Type 874-MR Mixer Rectifier (see Paragraph 3.33) is to be used as the detector, it is mounted directly on the left-hand connector on the probe carriage, as indicated in Figure 12. No connection is made to the other connector on the carriage. If a receiver (see Paragraph 3.34) is to be used as a detector, a length of double-shielded cable fitted with coaxial connectors should be used to connect the left-hand connector on the carriage to the receiver input. A Type 874-R20 Patch Cord is suitable.

If the built-in crystal detector (see Paragraphs 3.31 or 3.32) is to be used, a Type 874-D20 Adjustable Stub should be inserted in the left-hand connector on the carriage and the shielded connection to the amplifier, attenuator, or microammeter made from the other connector using a Type 874-R31 or R32 Patch Cord, as shown in Figures 10 and 11.

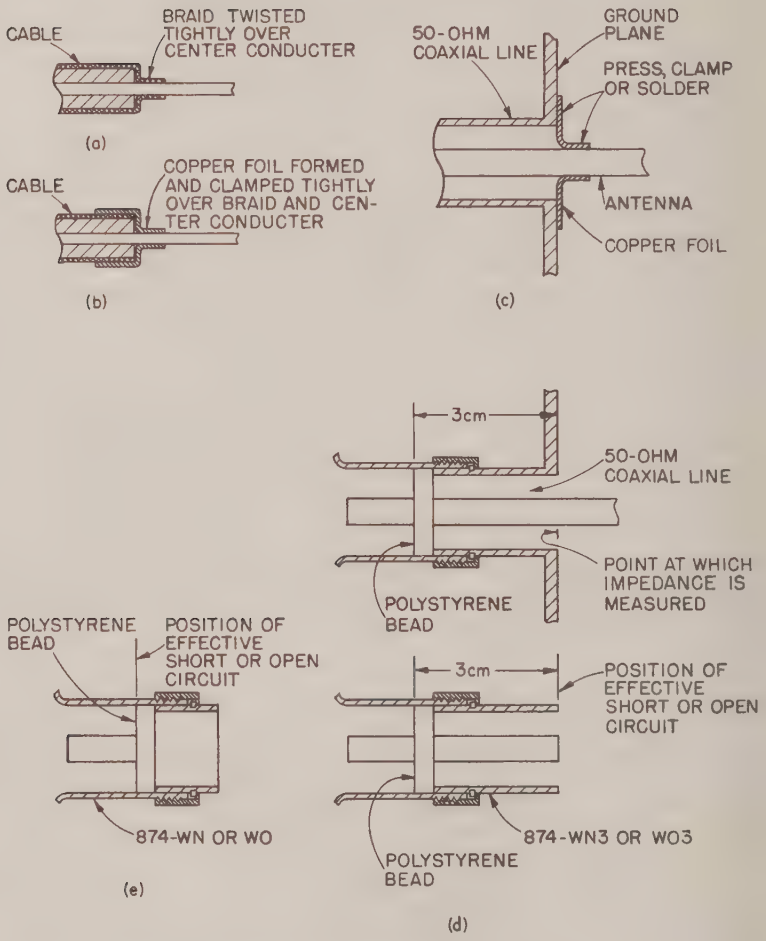
4.11 Coaxial Adaptors: If the unknown, the generator, or the detector is fitted with connectors other than the Type 874 Connectors, the following constant-impedance adaptors can be used to make the transition to Type 874 Connectors.

TYPE NO.	CONNECTORS ON ADAPTORS	
874-QNP	874 connector on one end,	Type N Plug Connector on the other
874-QNJ	"	Type N Jack "
874-QBP	"	Type BNC Plug "
874-QBJ	"	Type BNC Jack "
874-QCP	"	Type C Plug "
874-QCJ	"	Type C Jack "
874-QUP	"	Type UHF Plug "
874-QUJ	"	Type UHF Jack "
874-QV2	"	1-5/8 -51.5Ω VHF Rigid Line "
874-QU3	"	3-1/8 -50.0Ω UHF Rigid Line "

NOTE: UHF connectors do not have a constant impedance and introduce an appreciable reflection in the line at the higher frequencies.

The VSWR of these adaptors is very low and, in most cases, the adaptor has no significant effect on the measurements.

Drawings are available for the modification of standard Type HN Connectors to transform them into adaptors to Type 874 Connectors.



(a) Short-circuiting a cable with its own braid.
(b) Short-circuiting a cable with copper foil.
(c) Short-circuiting an air line with copper foil.
(d) Use of Type 874-WN3 Short-Circuit Termination Unit or Type 874-WO3 Open-Circuit Termination Unit to make a short circuit or open-circuit when measuring point is located 3 cm from front face of bead, as in upper figure. Upper unit is similar to a Type 874-M Component Mount.
(e) Position of the short- or open-circuit when a Type 874-WN Short-Circuit Termination Unit or Type 874-WO Open-Circuit Termination Unit is used.

Figure 14. Methods of Short- and Open-Circuiting Cables and Air Lines.

4.12. Methods of Short- and Open-Circuiting a Line: The method of producing the short-circuit for the line-length measurement or adjustment is important. In cases in which an antenna or other element terminating a line is being measured, the short-circuit may be made by wrapping a piece of copper foil around the inner conductor and binding it to the outer conductor of the outer conductor of the feed line at its end, as shown in Figure 14c.

It is more difficult to obtain an accurate open-circuit on a line than a short-circuit, as the fringing capacitance at the end of the center conductor will effectively make the line appear to be longer than it really is, and hence will cause errors, unless compensated for. The fringing capacitance is compensated for in the open-circuit termination units mentioned below.

A more satisfactory method of producing a short-circuit or open-circuit is to use a Type 874-WN or WN3 Short-Circuit Termination or Type 874-WO or WO3 Open-Circuit Termination Unit. The Type WN3 and WO3 units produce a short- or open-circuit a physical distance of 3 cm from the front face,[7] the measuring instrument side, of the insulating bead as shown in Figure 14. Hence, if the device under test is fitted with a Type 874-B Connector and a length of 50-Ohm Air Line[8] in which the physical distance between the front face of the insulating bead and the point at which the measurement is desired is exactly 3 cm, the circuit under test can be disconnected and a Type 874-WN3 or Type 874-WO3 Short- or Open-Circuit Termination Unit connected for the line-length measurement. This arrangement produces very accurate results.

The Type 874-WN or -WO Termination Units produce a short- or open-circuit directly at the front face of the insulating bead. These units can be used even if the impedance is desired at a point on the line, other than at the face of the bead, if the electrical distance between the two points is added to or subtracted from the line length measured with the short- or open-circuit termination units connected. The electrical line length for air dielectric line is equal to the physical length divided by the wavelength. Each bead in the Type 874 Connector effectively adds 0.20 cm to the length in addition to its physical length.

If the impedance is desired at the input to a coaxial circuit connected to the slotted line, a Type 874-WN Short-Circuit can be used to produce a short-circuit directly at the front face of the insulating bead in the Type 874 Connector on the circuit under test. (The front face of the bead is located at the bottom of the slots in the outer connector.)

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[7] The front face of the bead is located at the bottom of the slots between the contacts on the outer connector. Hence, its position can be easily determined from the outside of the connector.

[8] The coaxial-line section of a Type 874-M Component Mount can be used for this purpose, or a Type 874-WN3 Short Circuit or a Type 874-L10 Air Line can be modified to be suitable.

4.2 DETECTOR TUNING

4.21 Crystal Rectifier Tuning: The crystal rectifier built into the carriage is tuned by means of the adjustable stub, which is effectively connected in parallel with it in order to increase the sensitivity and to provide selectivity. In operation, the stub is adjusted until maximum output is indicated by the detector.

In tuning the stub, one must be careful not to tune it to a harmonic of the desired signal rather than to the fundamental. Confusion may result in some cases if the tuning is done with a high VSWR on the line, as the minima of the harmonics may not be coincident with the minima of the fundamental and, consequently, the harmonic content of the signal picked up by the probe may be several orders of magnitude greater than that present in the local oscillator output. To minimize the possibility of mistuning, the probe should be tuned with a low VSWR on the line, for instance, with the line terminated in a Type 874-WM Termination Unit or with the load end of the slotted line open-circuited. In the open-circuit case, the minima of the harmonics fall very close to the fundamental minima and, hence, the possibility of confusion is small even though the VSWR is high. As a check, the distance between two adjacent voltage minima on the line can be measured. If the stub is tuned correctly, the spacing should be half a wavelength.

With the Type 874-D20 Adjustable Stub, the crystal can be tuned to frequencies from about 250 Mc to above 5000 Mc. In the vicinity of 3000 Mc the crystal is self-resonant, and the effective Q of the probe circuit is low and the tuning rather broad. For operation at frequencies below 250 Mc, a Type 874-D50 Adjustable Stub can be used down to 150 Mc or various lengths of Type 874-L Air Lines can be inserted in series with the adjustable stub. Smoother carriage operation is obtained when the low-frequency stub is used if the line is tilted forward slightly, making the stub stand more nearly vertical.

4.22 Mixer Rectifier Tuning: When a mixer rectifier is used as a detector (and also when a superheterodyne receiver is used), care must be taken to tune the local oscillator to beat with the desired signal and not with one of its harmonics. Harmonics of the oscillator signal will beat with harmonics of the signal picked up from the slotted line and produce an output at the intermediate frequency if the local oscillator is mistuned from the proper frequency. Proper settings of the local oscillator are given by the following expression, assuming that the intermediate frequency is 30 Mc.

$$f_{LO} = \frac{f_S \pm 30}{n} \qquad (17)$$

where f_{LO} is the frequency of the local oscillator, f_S is the signal frequency and n is an integer corresponding to the harmonic of the local oscillator signal used. For best results, the lowest possible harmonic of the oscillator should be used.

If $n = 1$, there are two possible settings of the local oscillator separated by 60 megacycles and centered about the signal frequency. If $n = 2$, the two

possibly settings are separated by 30 Mc and centered about $f_S/2$. In the general case, the two possible settings are separated by 60/n and centered about the frequency f_S/n.

The second harmonic of the desired signal frequency will produce a beat frequency of 30 Mc when the local oscillator frequency is

$$f_{LO} = \frac{2f_S \pm 30}{n} = \frac{f_S \pm 15}{n/2} \qquad (18)$$

or, in general,

$$f_{LO} = \frac{f_S \pm \frac{30}{h}}{\frac{n}{h}} \qquad (19)$$

where h is the harmonic of the signal frequency. It can be seen from the above equation that some of the harmonic responses may be located reasonably close to the frequency at which the fundamental is detected. The higher the harmonic of the local oscillator used, the closer will be the spurious responses.

In general, spurious responses do not cause much difficulty, as the frequency to which the detector is tuned can be easily checked by measuring the distance between two voltage minima on the line, which should be half a wavelength at the operating frequency.

4.3 PROBE PENETRATION ADJUSTMENT

The probe penetration should be adjusted to give adequate sensitivity and yet not have a significant effect on the measured VSWR. The presence of the probe affects the VSWR because it is a small capacitance in shunt with the line. It has the greatest effect at a voltage maximum where the line impedance is high.

The probe penetration can be adjusted by removing the tuning stub connected to the left-hand connector and turning the small screw found inside the inner connector. (See Figure 9.) Clockwise rotation of the screw increases the coupling. In most cases in which moderate VSWR's are measured, a penetration of about 30% of the distance between the two conductors gives satisfactory results. The coupling can be adjusted to 30% by increasing the coupling until the probe strikes the center conductor of the slotted line and then backing it off six full turns of the screw. The point of contact between the probe and the center conductor is most easily measured by connecting an ohmmeter between the inner and outer conductors of the line and noting when the resistance suddenly drops from a very high value to a reasonably low value. The crystal is in series with this circuit so the resistance will not drop to zero. No indication will be obtained if the crystal has been removed. Do not screw the probe down tight against the center conductor, as it will damage the probe.

The amount of probe penetration can be visually checked by looking through the slot from one end of the line at the probe.

The effect of the probe coupling on the VSWR can be determined by measuring the VSWR with one probe coupling and then increasing the coupling and remeasuring the VSWR. If the measured VSWR is the same in both cases, the probe coupling used has no significant effect on the measurement. If the measured VSWR's are different, additional measurements should be made with decreasing amounts of probe penetration until two similar measurements are obtained. However, as pointed out in the previous paragraph, a 30% coupling usually gives satisfactory results except when the VSWR is high and a larger coupling is usually required.

The probe coupling or the oscillator output should be adjusted until the output from the detector is in a satisfactory range. If the crystal detector is used, this means the maximum output to be measured should not correspond to an input beyond the square-law range if the square-law characteristic is to be depended upon (see Paragraph 3.31), and the probe coupling should not be large enough to affect the measurements appreciably.

4.4 MEASUREMENT OF WAVELENGTH

The wavelength of the exciting wave in air can be measured using the slotted line by observing the separation between adjacent voltage minima when the line is short- or open-circuited. As explained in Paragraph 2.2, the spacing between adjacent minima, d, is one-half wavelength or

$$\lambda = 2d \tag{20}$$

For greater accuracy at the higher frequencies, the distance over a span of several minima can be measured. If the number of minima spanned, not counting the starting point, is n, then

$$\lambda = \frac{2d}{n} \tag{21}$$

4.5 MEASUREMENT OF CIRCUITS HAVING LOW VSWR'S

If the standing-wave ratio on the line is less than 10 to 1, the VSWR is usually determined by actually measuring the relative amplitudes of a voltage maximum and a voltage minimum (see Paragraph 3.3). To do this, the carriage containing the probe can be moved along the line by lightly pressing downward and turning the knob mounted on the base of the carriage, or by grasping the body of the carriage at the base of the knob with the thumb and forefinger and pushing in the desired direction of motion. The relative amplitudes of the voltage maximum and minimum and the position of the voltage minimum can be determined in this manner. For maximum accuracy, the carriage should

be moved by pushing the carriage from its base in one direction only through the maximum or minimum, as a small change in probe coupling may occur with a change in direction of motion or as a result of pressing down on the knob. This change is usually less than 0.05 db.

The probe coupling can vary a maximum of $\pm$2-1/2% along the line and hence the VSWR measured is in error by the difference in coupling coefficients at the maximum and minimum voltage points. This error can be avoided by calibrating the variation of coupling with probe position, as outlined in Paragraph 5.2, or can be reduced greatly by measuring several minima and several maxima and averaging the results. The coupling usually changes the most near the ends of the line and, hence, better accuracy usually can be obtained if measurements close to either end are avoided.

For a particular setup, a check must be made to determine whether the crystal is operating in the square-law range and whether the sensitivity is adequate. This is done by connecting the circuit to be tested and setting the probe to a voltage maximum. If the meter and the Type 1231-B Amplifier can be brought on scale with the amplifier set at maximum sensitivity and with an attenuation of less than 30 db in the Type 1231-B-P4 Attenuator, the crystal will be operating in the square-law range (assuming 50% modulation). The probe is then moved to a voltage minimum, and if the meter reading under these conditions is greater than about one-fourth of full scale with any setting of the Type 1231-B-P4 Attenuator, the r-f input to the line is adequate. If a one-fourth full-scale meter reading cannot be obtained, even with the attenuator set at zero, the r-f input to the line should be increased. If the r-f input cannot be increased, the probe coupling should be increased. (See Paragraph 4.3.) If either the r-f input or the probe coupling are increased, the voltage maximum point should be rechecked to make sure that the crystal is still operating in the square-law range. If the meter indication at the voltage maximum is greater than full scale with the attenuator set at 30 db, and the meter indication at the voltage minimum is less than one-third of full scale with the attenuator set at zero, the VSWR on the line is greater than 20 db and the width-of-minimum method, described in Paragraphs 4.6 and 4.722, should be used.

If the impedance of the unknown is desired, the VSWR and the electrical distance between a voltage minimum on the line and the unknown must be determined and the unknown impedance calculated, as outlined in Paragraphs 2.32 or 2.33.

The effective distance to the unknown can be measured by short-circuiting the line with a very low inductance short at the unknown (see Paragraph 4.12) and measuring the position of a voltage minimum on the line. This minimum is an integer number of half-wavelengths from the unknown. Since the impedance along a lossless line is the same every half-wavelength, the position of the voltage minimum found with the line short-circuited is the effective position of the unknown. If the line is very long, oscillator frequency shifts (discussed in Paragraph 4.62) may be serious.

If a series of measurements are to be made on the same circuit, it may be desirable to determine the actual effective length of the line in centimeters

between a reference point on the scale on the slotted line and the unknown and thus eliminate the necessity of short-circuiting the unknown for each frequency. If the position of the minimum with the line short-circuited at the unknown is measured at one frequency, the point at which the minimum is found on the line must be $n\lambda/2$ wavelengths from the unknown. If the line is not too many wavelengths long, the effective length can be estimated from the physical length of the line, multiplied by the square root of the dielectric constant of the line insulation, with an accuracy of better than a quarter-wavelength. The value of the integer n can then be determined by comparing the estimated length with the possible values of $n\lambda/2$. At other frequencies, the electrical distance between the measured position of the minimum on the slotted line and the unknown can then be determined from the sum of (1) the distance between the unknown and the reference point on the line, and (2) the distance between the reference point and voltage minimum, all divided by the wavelength at the operating frequency. If the line is many wavelengths long, the frequency must be known very accurately if the electrical distance to the unknown is to be determined from the frequency and the physical length.

When the VSWR is very low, the minima will be very broad, and it may be difficult to locate their positions accurately. In this case, better results usually can be obtained by measuring the positions of points on either side of a voltage minimum at which the voltage is roughly the mean of the minimum and maximum voltages, as shown in Figure 15. The minimum is located midway between these two points.

If the line between the unknown and the slotted line has a significant amount of loss, the effect of the loss on the unknown impedance can be corrected for, as outlined in Paragraph 4.61.

Harmonics of the oscillator frequency may also cause trouble, as discussed in Paragraph 4.63. The effect will tend to be most serious when the VSWR at the harmonic frequencies is high.

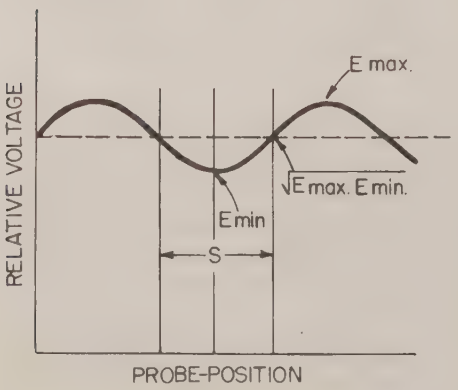

Figure 15. Method of improving the accuracy of the determination of the position of a voltage minimum on the line when the VSWR is low.

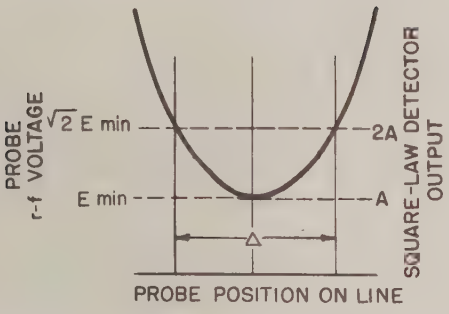

Figure 16. Method of measuring the width of the voltage minimum for VSWR determinations when the VSWR is high.

4.6 MEASUREMENT OF CIRCUITS HAVING HIGH VSWR'S

When the VSWR on the line is 10 to 1 or more, direct accurate measurements of a voltage maximum and a voltage minimum are difficult because of the following reasons:

(1) The effect of a fixed probe-coupling coefficient on the measurement increases as the VSWR increases because the line impedance at the voltage maximum increases, and the shunt impedance produced by the probe has greater effect.

(2) As the VSWR increases, the voltage at the voltage minimum usually decreases and, hence, a greater probe-coupling coefficient is required to obtain adequate sensitivity. The increased probe coupling may cause errors as outlined in (1).

(3) The accuracy of the measurement of the relative voltage decreases as the VSWR increases. The voltage range becomes too great to permit operation entirely in the square-law region. With the Type 1231-B Amplifier, Type 1231-P2 Tuned Circuit, and the Type 1231-P4 Adjustable Attenuator, an r-f input voltage range of about 10 to 1, or 20 db, is obtainable with the 50% modulation in the square-law region when the output meter is set to the 10 db point on the meter scale, with the amplifier set to maximum sensitivity and the adjustable attenuator set to zero attenuation at a voltage minimum.

Accurate measurements of VSWR's greater than 10 can be made using the width-of-minimum method. This is essentially a resonance method and is similar to measuring the Q of a circuit by measuring the frequency increment between the two half-power points. In the slotted line case, the spacing, Δ, between points on the line at which the r-f voltage is $\sqrt{2}$ times the voltage at the minimum is measured, as shown in Figure 16. The VSWR is related to the spacing, Δ, and the wavelength, λ, by the expression

$$\text{VSWR} \cong \frac{\lambda}{\pi\Delta} \qquad (22)$$

If the detector is operating in the square-law region, $\sqrt{2}$ times the r-f voltage corresponds to twice the minimum rectified output or a 6-db change in output.

For very sharp minima, the width of the minimum can be measured to a much greater accuracy by using the Type 874-LV Micrometer Vernier, than by means of the centimeter scale on the slotted line. The vernier can be read to $\pm$ 0.002 cm. When the vernier is used, the probe is moved slightly to the right of the minimum and the vernier adjusted to have its plunger strike the carriage on the unpainted surface below the output connector. The position of the vernier is adjusted by loosening the thumb screw which clamps the vernier to a reinforcing rod, sliding it along to the proper position, and relocking it.

The probe is then driven through the minimum and the twice-power points by turning the micrometer screw. The output meter reading corresponding to the minimum is determined and then the Type 1231-P4 Attenuator set for 6 db more attenuation.

The micrometer is then backed off again and the probe returned to the right side of the minimum. The probe is then driven through the minimum and twice-power points again and the two micrometer readings corresponding to the original output meter reading noted. The difference between these readings is equal to Δ.

If the minimum is too close to the right-hand end of the line to permit the vernier being used in the usual manner, the vernier can be moved to the left-hand side of the carriage and the other end of the plunger used to drive the carriage.

The electrical distance between the unknown and the minimum found on the line can be determined as outlined in Paragraph 4.5.

At very high standing-wave ratios, the losses in the slotted line and in any connecting line or cable used may have an appreciable effect on the measurements. To keep this error as low as possible, the voltage minimum nearest the load should be measured. The effect of the loss in the line can be corrected for as outlined in Paragraph 4.61.

4.61 Correction for Loss in Line Between Measuring Point and Unknown: When a load is connected to the slotted line through a length of air line or cable, the loss in the air line or cable may appreciably affect the measurements. Loss in the cable tends to make the measured VSWR less than the true VSWR produced by the load.

The amount of loss in a length of cable can be estimated from published data or measured using a slotted line. The loss can be measured by determining the VSWR with the load end of the line open-circuited[9] and shielded to prevent radiation losses. The total attenuation, $\alpha\ell$, in the length of cable is:

$$\tanh \alpha\ell = \frac{1}{(\text{VSWR})_{oc}} \qquad (23a)$$

[9] An open-circuited line is used for this measurement to eliminate the significant losses present in most short-circuiting devices. A Type 874-WO Open Circuit is useful for this purpose.

$$\alpha\ell = \tanh^{-1}\frac{1}{(VSWR)_{oc}} \quad \text{nepers} \qquad (23b)$$

$$= 8.686\tanh^{-1}\frac{1}{(VSWR)_{oc}} \quad \text{db.} \qquad (23c)$$

where VSWR is expressed as a ratio, not in db.

If VSWR is greater than 10,

$$\alpha\ell \cong \frac{1}{(VSWR)_{oc}} \text{ nepers} = \frac{8.686}{(VSWR)_{oc}} \text{ db.} \qquad (24)$$

The attenuation can also be determined from the open-circuited VSWR using the TRANSMISSION LOSS AND STANDING WAVE RATIO scales located below the Smith Chart, shown in Figure 17. The point corresponding to the open circuit VSWR is located on the $\frac{E_{max}}{E_{min}}$ or DB scales under STANDING WAVE RATIO. At the same distance from the center, find a corresponding point on the TRANSMISSION LOSS scale. Attenuation of the line is equal to the number of decibels between the left-hand end of the scale labeled 1 DB STEPS and this latter point. The scale is marked off in 1 db steps.

In most cases the loss in the slotted line itself can be neglected, but the loss in the line or cable used to connect the slotted line and the load is of importance. The unknown impedance can then be calculated in the same manner as for the lossless case by first correcting the measured voltage standing-wave ratio, $(VSWR)_m$, for the effect of the loss in the line. The effective voltage standing-wave ratio, $(VSWR)_e$, is then

$$(VSWR)_e = \frac{(VSWR)_m - \frac{1}{(VSWR)_{oc}}}{1 - \frac{(VSWR)_m}{(VSWR)_{oc}}} \qquad (25)$$

If the loss in the slotted line is of importance, a correction must be made for the loss in the slotted section between the points at which the voltage minima are found with the load connected and with the line open-circuited. The loss in the slotted section can be determined by a measurement of VSWR of the slotted section alone with a shielded open-circuit termination. The loss in nepers per unit length is $\frac{1}{(VSWR)_{oc_{sl}} \times \ell_{oc}}$ where ℓ_{oc} is the distance between the open

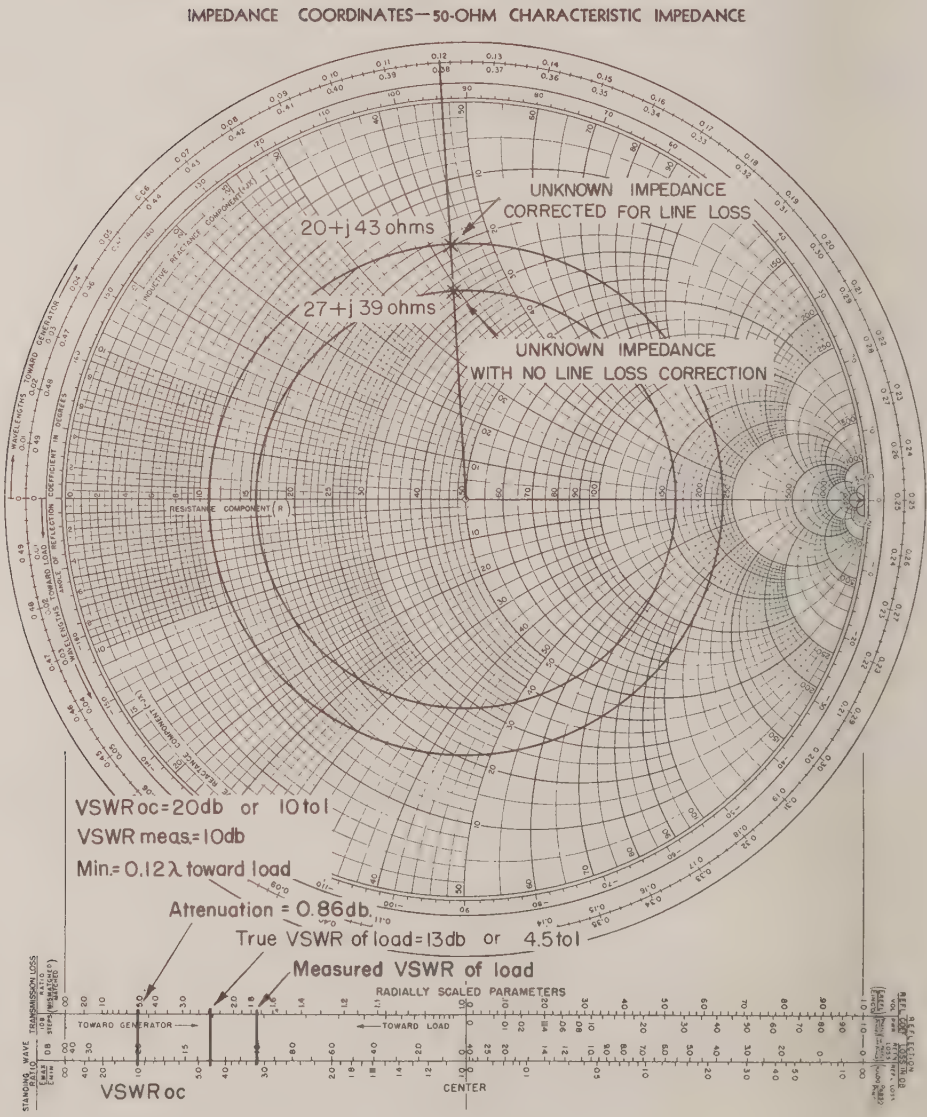

Figure 17. Example of the use of the Smith Chart for line length corrections when the line has an appreciable amount of loss. (See Paragraph 4.61.)

circuit and the point at which the VSWR is measured. The over-all line loss can be corrected for this effect by use of the equation

$$\frac{1}{(\text{VSWR})_{\text{oc}_{\text{eff}}}} \cong \frac{1}{(\text{VSWR})_{\text{oc}_{\text{unk}}}} \pm \frac{1}{(\text{VSWR})_{\text{oc}_{\text{sl}}}} \times \frac{\Delta \ell}{\ell_{\text{oc}}} \qquad (26)$$

where $\Delta \ell$ is the distance between the minimum with the load connected and the minimum with the slotted line open-circuited, and $(\text{VSWR})_{\text{ocunk}}$ is the VSWR measured with the load open-circuited. The $\pm$ sign is positive when the minimum measured with the load connected is closer to the generator than is the minimum measured with the load disconnected, and vice versa.

The unknown impedance can be calculated using the Smith Chart exactly as outlined in Paragraph 2.332 if the measured VSWR is corrected as indicated in Equation (25); or the complete correction procedure can be carried out on the Smith Chart and the need for the solution of Equation (25) eliminated, if desired, in the following manner. First, the point corresponding to the measured VSWR is determined on the scale marked STANDING WAVE RATIO, located below the chart, and the corresponding point on the TRANSMISSION LOSS, 1 DB STEPS scale is found. A new point is found on this scale by traveling outward, TOWARD LOAD, a distance corresponding to the db attenuation in the line. The radius of the circle drawn on the Smith Chart is the distance from this point to the center of the scale. The unknown impedance is found on this new circle at an angle from the resistance axis corresponding to the electrical distance to the load, as outlined in Paragraph 2.332.

For example, suppose the measured open-circuit SWR is 20 db, the SWR with the load connected is 10 db, and the minimum with the load connected is 0.12 wavelength on the load side of the short-circuit minimum. The attenuation, $\alpha \ell$, in the length of cable is 0.86 db. The point on the STANDING WAVE RATIO scale for a SWR of 10 db is located as shown on Figure 17, and the corresponding point is found on the TRANSMISSION LOSS 1-DB STEPS scale. A new point on the TRANSMISSION LOSS scale 0.86 db (0.86 division) toward the left-hand end of the scale is found and a line is drawn from this point to the STANDING WAVE RATIO scale. The reading of the scale at this point is 4.5 or 13 db, which is the true VSWR.

Corrections can also be made using the following transmission-line equations (from Equations (14a) and (14b)):

$$R_x = Z_0 \times \frac{2(\text{VSWR})_e}{\left[(\text{VSWR})_e^2 + 1\right] + \left[(\text{VSWR})_e^2 - 1\right]\cos 2\theta} \qquad (27)$$

$$X_x = -Z_o \times \frac{\left[(VSWR)_e^2 - 1\right] \sin 2\theta}{\left[(VSWR)_e^2 + 1\right] + \left[(VSWR)_e^2 - 1\right] \cos 2\theta} \qquad (28)$$

where θ is the electrical distance between the minima with the line short-circuited and with the load connected. It is positive when the load minimum is on the generator side of the short-circuit minimum. When both VSWR's are greater than 10, and θ is not approximately n x 90°, where n is an odd integer, $\left(\frac{\tan\theta}{VSWR} < 0.1\right)$, the following approximation is valid:

$$R_x \cong \frac{Z_o}{(VSWR)_e \cos^2\theta} \qquad (29)$$

$$X_x \cong -Z_o \tan\theta \qquad (30)$$

The equations are much more accurate than the Smith Chart, particularly when the VSWR is high.

As an example, suppose the open-circuit standing-wave ratio is 30 db, or 31.6 to 1, the VSWR with the unknown connected is 25 db or 17.77 to 1, and the minimum with the unknown connected is located 0.17 wavelength on the generator side of the short-circuit minimum. Then,

$$R_x \cong \frac{50}{40.5 \cos^2(360° \times 0.17)} = 5.32 \text{ ohms}$$

$$X_x \cong -50 \tan 61.2° = -90.9 \text{ ohms}$$

4.62 Oscillator Frequency Shifts: If the effective position of the unknown is determined by short-circuiting the unknown and measuring the position of a voltage minimum, errors may be caused in some cases by shifts in the oscillator frequency with the change in the load impedance between the short-circuit and loaded conditions. The effect can become more serious as the length of line between the load and the slotted line is increased. Oscillators which are tightly coupled to the line can have relatively large frequency shifts. The effect can be greatly reduced by inserting a pad, such as a Type 874-GG

10-DB Pad, between the oscillator and the slotted line. If the resultant decrease in input cannot be tolerated, the oscillator tuning can be adjusted to compensate for the frequency shift. The oscillator frequency can be checked using a receiver or a heterodyne frequency meter such as a General Radio Type 720-A. Signal generators, in general, are loosely coupled, and the frequency shift is usually small.

4.63 Harmonics: Another possible source of error in the measurement of high standing-wave ratios is the presence of harmonics in the wave traveling along the line. Harmonics can be generated by the driving oscillator or by a non-linear unknown such as a crystal rectifier. The minima for the harmonics will not necessarily appear at the same points along the line or have the same relative amplitudes as the fundamental minima, and, hence, a small harmonic content in the signal may produce a harmonic signal many times that of the fundamental at a minimum point. Therefore, if the detector will respond at all to harmonics, difficulty may be encountered. Superheterodyne receivers and the mixer rectifier detector, in general, have excellent harmonic rejection; but the tuned crystal detector may not have a large amount of rejection for various harmonics because the tuning stub has higher order resonances. When the crystal detector is used for measurements of high VSWR's, and preferably even when a receiver is used, a good low-pass filter, such as the Type 874-F500 or F1000 Low-Pass Filter, is required between the oscillator and the line to reduce the harmonics to an insignificant value. A good superheterodyne receiver or a mixer rectifier is recommended when the VSWR is very high.

4.64 Frequency Modulation: The presence of appreciable frequency modulation on the applied signal may also have a serious effect on the results when the high standing-wave ratio is very high. Frequency modulation is usually produced when a high-frequency oscillator is amplitude-modulated; but, in oscillators using filament-type tubes, frequency modulation can also be caused by the filaments when heated with a-c power. The amount of frequency modulation for a given degree of amplitude modulation usually increases as the oscillator frequency approaches its upper limit. The Type 1209-A Unit Oscillator and Type 1021-AU Signal Generator are satisfactory for modulated signal measurements on very high VSWR's at 50% modulation up to about 750 Mc. At the higher frequencies, reasonably large errors are produced in measurements of standing-wave ratios of the order of 500 or 1000. At standing-wave ratios below 50, the error is usually negligible if the over-all line length is short.

4.7 MEASUREMENT OF 50-OHM COAXIAL LINE CIRCUITS

In coaxial-line measurements, the VSWR on the line, the impedance seen looking into an unknown line, or the impedance at the far end of a line may be desired. For instance, in measurements on antennas, either the VSWR on a line terminated in the antenna or the actual antenna impedance is desired. However, in most cases it is not possible to connect the antenna directly to the slotted line and an intermediate length of cable or air line must be used. The line or cable used should have a 50-ohm characteristic impedance. Lengths of Type 874-A2 Cable can be used for this purpose. The connecting cable has

no effect on the VSWR if it is a lossless uniform line, and hence the VSWR produced by the load is the same as that measured on the slotted line. In practice, however, the connecting cable and connectors will not be absolutely uniform but will have small discontinuities which will have some effect on the VSWR. The uniformity of lengths of Type 874-L Air Line is much better than that of coaxial cable and should be used if possible when the most accurate results are desired. There is, also, always some loss in the connecting cable. If it is significant, it can be corrected for as outlined in Paragraph 4.61.

4.71 Measurement of VSWR on a 50-Ohm Line: When the VSWR setup on a 50-ohm line terminated in the unknown is desired, the following procedure can be used.

(1) Set up the equipment and the tune detector, as outlined in Paragraphs 4.1, 4.2, and 4.3.

(2) Connect the unknown directly to the slotted line, if possible, or use lengths of 50-ohm air lines or cable provided with constant-impedance connectors, such as the Type 874 Connectors. If the unknown is fitted with connectors other than Type 874 Connectors, use one of the adaptors listed in Paragraph 4.11.

(3) Check the output from the detector at a voltage minimum and maximum and determine whether the probe coupling and generator outputs are satisfactory, as outlined in Paragraphs 3.3 and 4.3. If the indicated SWR is greater than 20 db, only the voltage minimum need be measured, as the width-of-minimum method can be used.

(4) If the SWR is less than 20 db, measure the relative output from the detector at several minima and maxima. Actually, only one minimum and one maximum need be measured, but, due to the variations in probe coupling along the line, greater accuracy can be obtained by averaging several minima and maxima or by calibrating the probe coupling, as outlined in Paragraph 5.2. For maximum accuracy using the crystal detector and the Type 1231-B Amplifier with the Type 1231-P4 Attenuator, the difference in the attenuator settings producing the same meter indications at the minima and maxima should be recorded, rather than the difference in the meter readings obtained with a constant attenuator setting.[10] The SWR is half the average db difference in the outputs if the detector is square law, and equal to the average difference if the detector is linear. If the SWR is greater than 20 db, use the width-of-minimum method, outlined in Paragraph 4.6, to determine the SWR.

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[10] If the SWR is low, the attenuator can be adjusted to give slightly less than a full-scale meter deflection at a voltage maximum and the meter readings for the other voltage maxima and minima recorded. The average maximum and average minimum readings are calculated, and the change in setting of the attenuator required to produce a shift in the meter reading from the average maximum to the average minimum is recorded. This procedure may save time when many measurements are to be made.

4.72 Unknown Impedance Connected at the End of a 50-Ohm Line: When the actual load impedance is desired, the following procedure can be used.

(1) Set up the equipment and tune the detector, as outlined in Paragraphs 4.1, 4.2, and 4.3.

(2) Connect the unknown to the slotted line. If the unknown is fitted with connectors other than Type 874 Connectors, use one of the adaptors listed in Paragraph 4.11.

(3) Check the output from the detector at a voltage minimum and maximum and determine whether the probe coupling and generator output are satisfactory, as outlined in Paragraphs 3.3 and 4.3. If the indicated SWR is greater than 20 db, only the voltage minimum need be measured, as the width-of-minimum method can be used.

(4) If the SWR is less than 20 db, measure the relative output from the detector at several minima and maxima. Actually, only one minimum and one maximum need be measured, but, due to the variations in probe coupling along the line, greater accuracy can be obtained by averaging several minima and maxima or by calibrating the probe coupling, as outlined in Paragraph 5.2. For maximum accuracy using the crystal detector and the Type 1231-B Amplifier with the Type 1231-P4 Attenuator, the attenuator settings producing the same meter indications at the minima and maxima should be recorded, rather than the difference in meter readings.[10] The SWR is half the average db difference in the outputs if the detector is square law, and equal to the average difference if the detector is linear. If the SWR is greater than 20 db, use the width-of-minimum method, outlined in Paragraph 4.6, to determine the SWR.

(5) Measure the position of the voltage minimum nearest the load end of the line.

(6) Short-circuit the end of the line at the point of connection to the unknown, using a very low inductance metal sheet or strap, or a Type 874-WN3 or WN Short Circuit, as described in Paragraph 4.12. Then, find the position of a voltage minimum on the line with the line shorted and record the scale reading corresponding to the probe position (see Paragraph 4.5).

(7) Determine the difference in position, ℓ, between the minimum measured with the line shorted, or the unknown itself,[11] and the minimum measured with the unknown connected, and divide the result by the wavelength to obtain $\frac{\ell}{\lambda}$.

(8) Determine on the Smith Chart the radius of the circle on which the impedance must lie from the scale labeled STANDING WAVE RATIO, located at

[11] If several measurements are to be made at different frequencies on the same circuit, the over-all electrical line length between any point on the slotted line can be determined as outlined in Paragraph 4.5, and the line has to be short-circuited only once.

the bottom of the chart, and draw a circle having this radius on the chart, with its center at the center of the chart. (See Paragraph 2.332.) If desired, the transmission-line equations presented in Paragraph 2.32 can be used in place of the Smith Chart. (The 50-ohm impedance version is considered here.)

(9) Note whether the minimum found with the line shorted lies on the generator side or on the load side of the minimum found with the load connected. If the short-circuit minimum lies on the load side, travel around the circle along the WAVELENGTHS TOWARD LOAD scale the number of wavelengths from zero found in Step 8. If the minimum lies on the generator side, travel in the opposite direction along the WAVELENGTHS TOWARD GENERATOR scale. Draw a line from this point to the center of the chart.

(10) Find the impedance in ohms of the unknown from the coordinates of the intersection of the line drawn in Step 9 and the circle drawn in Step 8. If the admittance is desired, travel around the chart another 0.25 wavelength and draw another line to the center of the chart, or use the admittance chart as outlined in Paragraph 2.334. The coordinates of the intersection of this line with the circle multiplied by 0.4 are the components of the admittance of the unknown in millimhos.

4.721 Example of Antenna Impedance Measurement, Low VSWR: The antenna under consideration is a stub mounted perpendicular to a ground plane. At the ground plane the stub is connected to the center conductor of a short section of 50-ohm coaxial line which terminates in a Type 874 50-Ohm Connector. Since it is not practical to bring the slotted line close enough to the antenna to make a direct connection between the slotted line and the instrument, a 3-foot length of 50-ohm coaxial cable is used to make the connection. (For the best accuracy, the cable should be as short as possible and, if possible, sections of Type 874-L30 Air Line used in place of the cable.) A Type 1209-A Unit Oscillator modulated by a Type 1214-A Unit Oscillator is used as a generator, and a Type 1231-A Amplifier with a Type 1231-P2 Filter and a Type 1231-P4 Attenuator are used with the built-in crystal detector, and a Type 874-D20 Stub Line as a detector. The oscillator is set to operate at 750 Mc and the stub adjusted for maximum output with the cable disconnected from the slotted line. The probe penetration had been previously set at 30% (6 turns out from the center conductor), at which position it has no appreciable effect on the measurements.

The antenna is then connected and the checks made for square-law operation, as outlined in Paragraph 4.5. In this case, the meter on the amplifier read full scale with an attenuator setting of approximately 16 db at a voltage maximum and read full scale with an attenuator setting of approximately 11 db at a voltage minimum. Therefore, the crystal is operating in the square-law range, and no adjustments of the r-f input or probe coupling are required.

For an accurate measure of the VSWR, the probe is set to the voltage minimum[12] nearest the load, and the attenuator adjusted to produce a meter reading of 1 db. The attenuator reading and probe position at this point are found to be 1.72 db and 35.22 cm. The probe is then moved in one direction until a voltage maximum is found and the attenuator is readjusted to give the same meter reading as obtained at the voltage minimum.

The probe is then moved[13] to each of the voltage minima and maxima found on the line[14] and the attenuator is adjusted to give the reference meter reading. The attenuator readings obtained are 17.2, 22.5, 17.4, 22.7, 17.0, and 22.3 db. The SWR is half the average difference in the attenuator settings[10] or

$$1/2 \left[\frac{22.5 + 22.7 + 22.3}{3} - \frac{17.2 + 17.4 + 17.0}{3} \right] = 2.65 \text{ db} .$$

The effective position of the measured minimum with respect to the load is then measured by short-circuiting the line at the antenna by means of a copper disk with a slot in it. The approximate position of the minimum is found and then the attenuator set to minimum attenuation to improve the resolving power. The minimum is still rather broad. To improve the accuracy, the oscillator input is increased. (The minimum position could also be determined more accurately by measuring the position of the two equal-output points, one on either side of the minimum, or by increasing the probe penetration.) In this case, the minimum occurred at 36.12 cm.

In order to calculate the antenna impedance, the wavelength must be accurately known. It can be determined from the frequency by the equation:

$$\lambda = \frac{3 \times 10^4}{f_{mc}} \quad \text{in cm}$$

where f_{mc} is the frequency in megacycles. It can also be measured on the line by measuring the distance between minima, as outlined in Paragraph 4.4. In the example under consideration, the wavelength was 40.00 cm.

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[12] With this low VSWR, the minima are relatively broad, and more accurate results could be obtained by finding the positions of points on either side of a minimum at which the voltage is the mean between the maximum and minimum voltage. The true position of the minimum is midway between these points (see Paragraph 4.5).

[13] In some cases, reversal of direction of the carriage causes a slight change in the probe coupling. For maximum accuracy, this can be eliminated by moving the carriage in one direction only.

[14] For greater accuracy, the variation in probe coupling could be calibrated, and corrections made, as outlined in Paragraph 5.2.

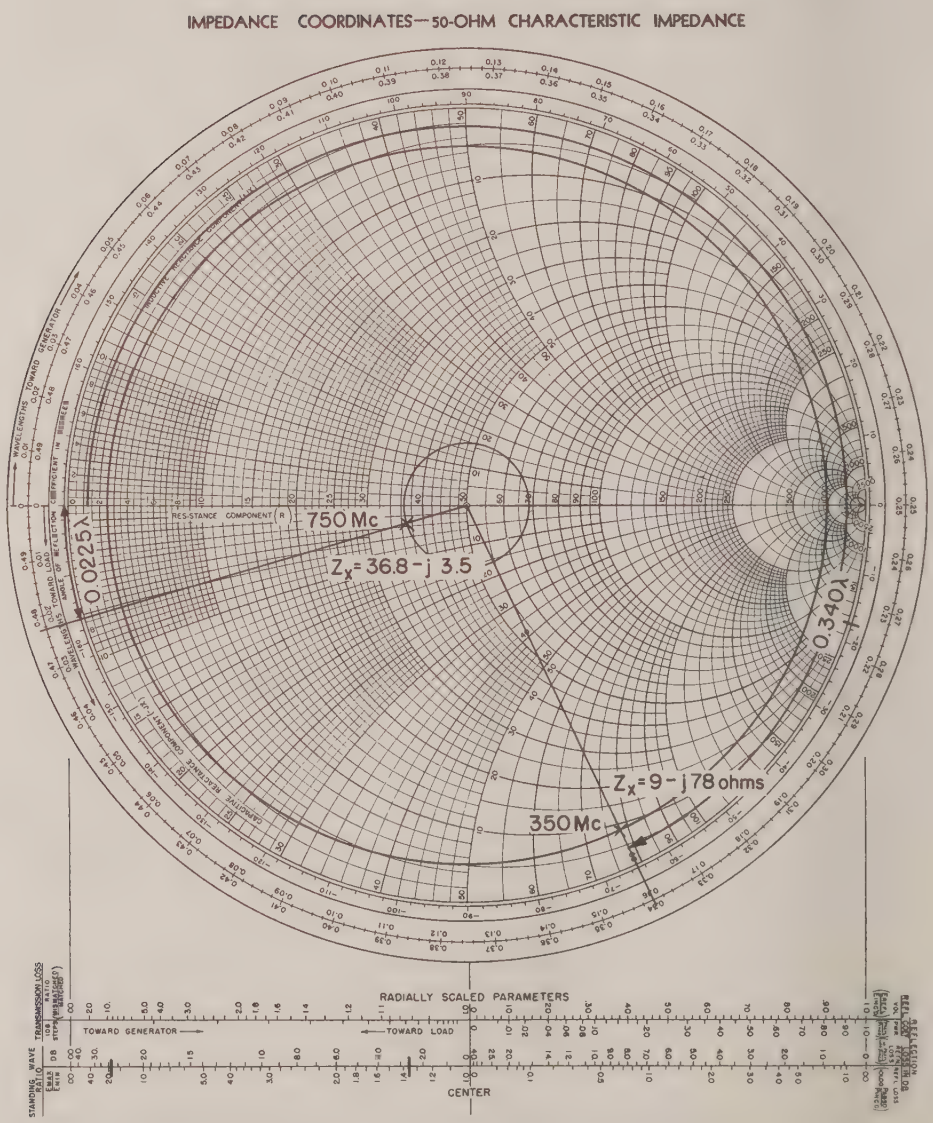

Figure 18. Example of the use of the Smith Chart to calculate antenna impedances. (See Paragraphs 4.721 and 4.722.)

The pertinent information, therefore, is:

SWR = 2.65 db
Position of minima with load connected = 35.22 cm
Position of minima with short-circuit at load = 36.12 cm
λ = 40.00 cm.

The impedance of the antenna is calculated as outlined in Paragraph 2.332. The radius on the Smith Chart, corresponding to 2.65 db, is found from the scales below the chart and the circle drawn on the chart, as shown in Figure 18. The position of the minimum with respect to the short-circuit minimum is $\frac{36.12 - 35.22}{40} = 0.00225$ wavelength toward the load. The antenna impedance is, therefore, 36.8 - j3.5 ohms.

In this case, the loss in the line between the antenna and the slotted line is negligible. In cases in which it is not, the loss can be corrected for as outlined in Paragraph 4.61.

4.722 Measurement of Antenna Impedance Having High VSWR: The same antenna measured in the previous example when measured at 350 Mc shows a high VSWR. The preliminary adjustments are the same as indicated in the previous example, but when the SWR is found to be greater than 20 db the width-of-minimum method is used. The probe is set to a voltage minimum near the load and the generator voltage increased to a maximum. If the meter still does not read at least half-scale at the voltage minimum with the Type 1231-P4 Attenuator at zero, the probe penetration is increased until it does. The input should not be more than required to obtain a half-scale reading with the attenuator set at 30 db. For greatest accuracy, the input or probe coupling should be adjusted to give at least a full-scale indication with the attenuator near zero.

To make the measurement, the probe is set at the voltage minimum and the attenuation is increased until the meter reads about half scale. The probe is then moved to the right of the minimum beyond the point at which the meter reads full scale. If the Type 874-LV Micrometer Vernier is available, it should be adjusted so the plunger contacts the unpainted surface on the edge of the carriage. The carriage is then moved continuously towards the left, using the micrometer vernier, or by hand, and the meter reading at the minimum noted. The attenuation of the Type 1231-P4 Attenuator is decreased to make the minimum read exactly 1 db on the meter, and then the attenuation of the Type 1231-P4 Attenuator is increased exactly 6 db[15] from this setting. The carriage is then slid to the right until the meter reads off scale, and then moved by means of the micrometer vernier, or by hand, to the left. The scale or vernier readings corresponding to the 1-db meter readings on each side of the null are recorded. The meter indication at the minimum should be the same as that obtained when the attenuation was originally increased by 6 db. If it is not, the attenuator is readjusted to make it the same.

[15] If the sensitivity is not great enough to obtain a 1-db meter reading, any other point on the meter scale can be used.

In the measurement in question, the minimum occurs at a scale reading of 42.40 cm and the micrometer vernier readings for the two 1 db meter readings are 2.111 and 0.632 cm. The distance between the twice-power points, Δ, is then 1.479 cm. The wavelength, λ, at 350 Mc is 85.7 cm. The VSWR from Equation (22) is then

$$\text{VSWR} = \frac{\lambda}{\pi\Delta} = \frac{85.7}{\pi \times 1.479} = 18.46$$

On short-circuiting the antenna, as outlined in Paragraph 4.5, a minimum is found at 13.09 cm. The antenna impedance is then calculated using the Smith Chart or the transmission-line equations, as outlined in Paragraphs 2.32 and 2.332. On the Smith Chart, the radius of the circle corresponding to a VSWR of 18.46 is drawn on the chart, as in Figure 18. The minimum with the antenna shorted is $\frac{42.20 - 13.09}{85.7} = 0.340$ wavelength toward the generator from the minimum found with the antenna unshorted. On traveling around the circle on the Smith Chart 0.340 wavelength toward the generator, the unknown impedand is found to be 9.0 - j78 ohms.

More accurate results can be obtained using the Equations (15a) and (15b) from Paragraph 2.32. Here $\theta = -360° \times 0.340 = -122.4°$, and $\tan\theta = 1.576$. Since $\frac{\tan\theta}{\text{VSWR}} \angle 0.1$ and the VSWR is greater than 10, the approximate form can be used. Also, θ is negative since it lies on the load side of the short-circuit minimum.

Therefore,

$$R_x = \frac{Z_o}{\text{VSWR}\cos^2\theta} = \frac{50}{18.46\cos^2(-122.4°)} = 9.4 \quad \text{ohms}$$

$$X_x = -Z_o\tan(-122.4°) = -78.8 \quad \text{ohms}$$

If the cable is long enough to have appreciable loss, corrections for loss can be made as outlined in Paragraph 4.61.

4.73 Measurement of the Input Impedance to Coaxial Line Circuits: The input impedance to a coaxial-line circuit can be measured by connecting the circuit directly to the slotted line by means of a coaxial connector and by then using the procedure outlined in Paragraph 4.72. In this measurement, the point in the connector at which the impedance is desired must be specified because the impedance may vary appreciably from one point to another in the connector. In many cases, it is advantageous to measure the impedance at the midpoint of

the connector. In order to determine the impedance at this point, the electrical distance from the connector midpoint and the position of a voltage minimum on the slotted line must be found.

The electrical distance can be determined by measuring the physical distance between the two points in question and adding 0.20 cm to the length obtained to account for the lower velocity of propagation in the polystyrene bead in the connector at the end of the slotted line.

Another more accurate method of determining the effective electrical distance is to short-circuit the end of the slotted line with a Type 874-WN Short Circuit and to determine the position of a voltage minimum on the slotted line, as outlined in Paragraph 2.32. The short-circuit is made at the face of the bead in this unit. To account for the difference in position between the face of the bead and the midpoint of the connector, the effective position of the minimum must be moved 1.0 centimeter towards the generator.

The VSWR is measured and the unknown impedance calculated as outlined in Paragraph 4.72.

4.8 MEASUREMENTS ON COMPONENTS AND LUMPED CIRCUITS

The Type 874-LB Slotted Line can be used to measure the impedance of components of all types. At high frequencies, this type of measurement is complicated by many factors, the most important of which generally are: (1) the position of the element with respect to ground, leads, and other circuit elements can have a large effect on the impedance of an element, and (2) the reactances of leads used, in addition to any leads which may be part of the component under test, to connect the component to the measuring device and the stray capacitance of the measuring terminals and supplementary leads, may also appreciably affect the measurements.

To minimize the effects of the first difficulty, the component should be measured while mounted in the position in the circuit in which it is to be used, or under as similar conditions as possible. One method of measuring a component in position in a circuit is to connect it to the slotted line by means of a length of flexible cable or rigid coaxial line, as shown in Figure 19. The rigid line is preferred as its characteristic impedance is more uniform. The impedance is measured, as outlined in Paragraph 2.332. The line is short-circuited at its load end by one of the methods shown in Figures 14a and 14b.

In order to minimize the effects of the lead and terminal reactances, the supplementary leads used to connect the component to the end of the coaxial line should be as short as possible.

The leads referred to do not include those normally used to connect the unknown to the circuit in which it is used. If the supplementary leads are short, the stray reactances can be considered as lumped into two elements: a shunt capacitance across the end of the line from the measuring instrument, and an inductance in series with the line, as shown in Figure 19. The lead and terminal reactances affect the measured impedance, Z_m, as can be seen from the

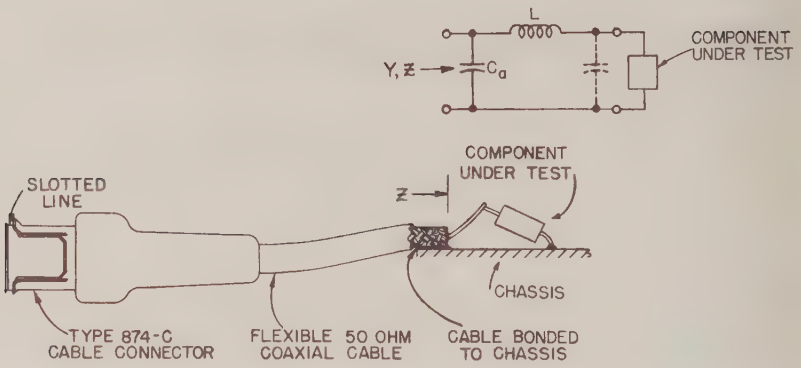

Figure 19. Approximate equivalent circuit of connecting lead reactances encountered when components are measured.

equivalent circuit in the figure. In order to determine the actual impedance of the unknown, the measured impedance should be corrected for the effects of the lead and terminal reactances, using the following equations:[16]

$$R_x = \frac{R_m}{D} \tag{31}$$

$$X_x = \frac{X_m\left(1 - \frac{X_m}{X_a}\right) - \frac{R_m^2}{X_a}}{D} - X_L \tag{32}$$

where

$$D = \left(1 - \frac{X_m}{X_a}\right)^2 + \left(\frac{R_m}{X_a}\right)^2 \tag{33}$$

$$X_a = -\frac{1}{\omega C_a} \quad \text{ohms} \tag{34}$$

$$X_L = \omega L \quad \text{ohms} \tag{35}$$

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[16] These will be recognized as the same equations that are used to correct for lead capacitance in the Type 916-A Radio-Frequency Bridge.

where L is the magnitude of the lead inductance in henries and C_a is the magnitude of the shunt capacitance in farads.

If the admittance of the unknown is desired, rather than the impedance, the admittance, Y_m, appearing across the end of the line, is calculated from the VSWR and position of a voltage minimum, as outlined in Paragraph 2.334, and the following equations used to correct for the lead reactances:

$$G_x = \frac{G_m}{D} \tag{36}$$

$$B_x = \frac{B'_m \left(1 - \frac{B'_m}{B_L}\right) - \frac{G^2_m}{B_L}}{D} \tag{37}$$

where

$$D = \left(1 - \frac{B'_m}{B_L}\right)^2 + \left(\frac{G_m}{B_L}\right)^2 \tag{38}$$

$$B'_m = B_m - B_a = B_m - \omega C_a \times 10^3 \quad \text{millimhos} \tag{39}$$

$$B_L = -\frac{10^3}{\omega L} \quad \text{millimhos} \tag{40}$$

where C_a and L are as defined in the previous paragraph. All admittance components are in millimhos.

The magnitudes of the lead and terminal reactances or susceptances can be determined from measurements of the reactance seen with the leads short-circuited by a low-inductance copper sheet at the point of connection to the unknown, and the reactance seen with the leads open-circuited at the point of connection to the unknown. The inductive reactance is measured when the leads are short-circuited and the capacitive reactance is measured when the leads are open-circuited. For this approximation to hold, the lead-capacitive reactance should be greater than five times the lead-inductive reactance.

A somewhat better approximation can be made by distributing the lead capacitance between the two ends of the leads, as shown by the dotted capacitor. The ratio of the two capacitances can be estimated from the physical configuration of the circuit.

An even better approximation can be made when the leads are reasonably long, if the inductance and capacitance are assumed to be uniformly distributed and the leads treated as a section of transmission line. The characteristic impedance, Z_0, of this line and the tangent of the electrical length, $\tan\theta$, are related to the short- and open-circuit impedances, Z_{oc}, and Z_{sc}, by the expressions:

$$Z_0 = \sqrt{Z_{oc} Z_{sc}} \tag{41}$$

$$\tan\theta = \sqrt{\frac{Z_{sc}}{Z_{oc}}} = \frac{X_{sc}}{Z_0} \tag{42}$$

Equation (12) or the Smith Chart can be used to correct the measured impedance for the effect of the equivalent section of transmission line. If a Smith Chart designed for lines having a 50-ohm impedance is used, the measured values should be divided by $\frac{Z_0}{50}$ before entering the chart and the resultant corrected impedance multiplied by $\frac{Z_0}{50}$. In most cases the capacitance is not uniformly distributed but the approximation usually gives reasonably accurate results. A normalized Smith Chart is better suited to this application.

In most cases more accurate measurements can be made by using the Type 874-M Component Mount, shown in Figure 20, on which the component or lumped circuit can be mounted. The end of the center conductor of a section of air line is used as the ungrounded terminal, and the outer conductor is extended in the form of a disk for a ground plane. The line can be short-circuited at the terminal by means of a very low inductance disk supplied, or the mount can be disconnected and replaced by a Type 874-WN3 Short-Circuit Termination Unit. The distance from the front face of the polystyrene bead in the connector mount is located 3 cm away from the ground plane surface; hence, the termination unit referred to places a short-circuit effectively at the ground plane surface when it is substituted for the component mount.

The reactance of supplementary leads must be corrected for, as previously outlined.

The coaxial-line section can be removed from the ground plate, if desired, by loosening the locking nut, and installed in any other plate if a 3/4-27 tapped hole is provided.

4.81 Example of Measurement of a 200-Ohm Resistor at 600 Mc: In this case, the resistor is mounted on a Type 874-M Component Mount, shown in Figure 20, which is connected to the slotted line. The tuned, built-in crystal, with a Type 1231-P4 Attenuator and a Type 1231-B Audio Amplifier, is used as a detector. A block diagram of the setup is shown in Figure 10. The stub is tuned with the slotted line open-circuited, as indicated in Paragraph 4.2. The unknown is connected and the input power adjusted to keep the maximum excursion of the crystal within the square-law range. The attenuator settings required to give full-scale readings on the meter for several maxima and average of the maxima and the average of the minima are taken as the true readings. Averages of several readings are taken to minimize the effect of the variation probe coupling along the line. The average of the maxima is 21 db, the average of the minima is 1 db, and the minimum is at a scale reading of 40.25 cm.

The component mount is then disconnected, the Type 874-WN3 Short Circuit is connected to the slotted line, and the position of a voltage minimum is measured. The position of the minimum nearest the load is found to be at 51.20 cm. Therefore,

$$\text{SWR} = \frac{21 - 1}{2} = 10.0 \text{ db}$$

$$\frac{\ell}{\lambda} = \frac{51.20 - 40.25}{50} = 0.219 \text{ wavelength}$$

The measured resistance and reactance calculated using the Smith Chart are: $R_m = 118$ ohms; $X_m = -66$ ohms.

In this case, the impedance directly across the ends of the resistor is desired. However, the resistor is connected to the mount by means of its own

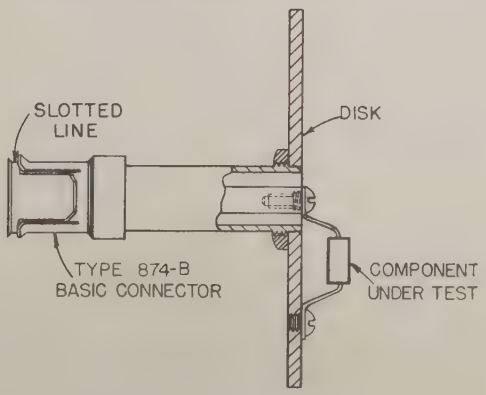

Figure 20. Sketch of the Type 874-M Component Mount.

leads which, of course, affect the measurements. Since it is not desirable to clip the leads at the ends of the resistor to measure the lead reactances, the resistor is removed and identical leads substituted. The position of the minimum on the line is determined with the leads open-circuited and is found to be 39.90 cm. The ends of the leads are short-circuited by spot-soldering a copper sheet about three inches in diameter to the ends of the leads and the minimum position again found. In this case it is at 32.95 cm.

The short-circuit reactance, X_{sc}, calculated from the Smith Chart, is +57 ohms. The open-circuit reactance, X_{oc}, is -330 ohms. The actual impedance appearing across the resistor terminals is then calculated using Equations (31) and (32).

$$R_m = 118 \text{ ohms}$$

$$X_m = -66.0 \text{ ohms}$$

$$X_L = X_{sc} = +57 \text{ ohms}$$

$$X_a = X_{oc} = -330 \text{ ohms}$$

$$D = \left(1 - \frac{-66}{-330}\right)^2 + \left(\frac{118}{330}\right)^2 = 0.768$$

$$R_x = \frac{118}{0.768} = 154 \text{ ohms}$$

$$X_x = \frac{-66\left(1 - \frac{-66}{-330}\right) - \frac{118^2}{-330}}{0.768} = -57 = -72.2 \text{ ohms}$$

The measured resistance is less than the d-c value of 200 ohms due to the shunt capacitance of the resistor itself.

Section 5.0 Miscellaneous

5.1 OPERATION AT FREQUENCIES BELOW 300 MC

Since the probe travel is only 50 cm, it will not always be possible to measure both a voltage minimum and maximum on the line at frequencies below 300 Mc as the range of travel of the probe is one-half wavelength 300 Mc. At frequencies below 150 Mc, where the line is less than a quarter of a wavelength, it will never be possible to measure both a voltage maximum and minimum on the line directly. If both a voltage minimum and maximum do not appear on the line at frequencies above 150 Mc, additional lengths of Type 874-L30 and L10 Air Lines can be inserted between the line and the load until both a minimum and a maximum do appear. Of course, if the VSWR is greater than 10, only the minimum need appear on the slotted section of line because the measurement can be made by the width-of-minimum method.

At frequencies below 150 Mc, lengths of air line can be inserted between the line and the load until either a minimum or maximum can be measured. Sections of air line are then transferred to the other side of the slotted line, that is, between the line and the generator, until the maximum or minimum appears and can be measured. The sections are transferred rather than removed to keep the load on the oscillator and, hence, the relative voltage amplitude on the line, constant.

A somewhat better solution is to use two slotted lines and add sections of air line between them or between one and the load until a minimum appears on one line and a maximum on the other. The probes are set at the respective maximum and minimum and the outputs from the detector and the position of the probe at the minimum recorded. A Type 874-WM Termination Unit is then connected to the end of the line and the outputs of the two detectors again recorded. Since the voltage is constant all along the line with the termination connected, the probe couplings in this case are proportional to the outputs if the detector is linear. If the detector is square-law, the probe couplings are proportional to the square root of the outputs. The outputs observed with the load connected can then be corrected for any difference in coupling. This calibration corrects for differences in probe penetration, differences in probe couplings, and differences in sensitivity of the detectors.

The Type 874-D20 Stub will tune the crystal rectifier down to 275 Mc. The Type 874-D50 Stub will tune down to 125 Mc. Additional lengths of air line can be inserted in series or in shunt using a Type 874 Tee for operation at lower frequencies. With the long stub in place, smoother operation of the carriage is obtained if the whole slotted line is tilted slightly forward to make the stub almost vertical.

5.2 CALIBRATION OF THE VARIATION IN PROBE COUPLING

The variation in probe coupling along the line can be calibrated and the measurements very easily corrected for the variations. A 1000-cycle signal from the audio oscillator having an output of at least 10 volts is applied to the slotted line whose load end is open-circuited. The tuning stub is removed and the amplifier input connected directly to the connector normally used for the tuning stub. The variation in indication on the meter on the amplifier is then recorded as a function of probe position. The curve thus obtained can be applied to r-f measurements. In this calibration, the crystal is not used and the output is directly proportional to the coupling. Therefore, the correction factor measured should be applied to r-f measurements after the square-law rectification characteristic has been corrected for.

The variations in probe coupling will change somewhat as the probe penetration is varied. Hence, for the most accurate results, the calibration curve should be made with the same probe penetration as used in the r-f measurements.

Section 6.0 Maintenance

6.1 REPLACING THE CRYSTAL RECTIFIER

The Type IN21-B Crystal Rectifier is mounted in the carriage, as shown in Figure 9.

It is held in place by means of a spring and can be removed by pulling it out of its socket after unscrewing the acorn nut on the back side of the carriage and removing the cover plate.

The crystal can be checked using an ordinary ohmmeter by measuring the resistance with both polarities of applied d-c voltage with the ohmmeter set on the X100 range. The resistance should be below 800 ohms in one direction and above 10,000 ohms in the other direction.

6.2 LUBRICATION AND CLEANING OF CARRIAGE TRACK

The slotted line should be kept in its storage box or covered when not in use to prevent the accumulation of dirt on the carriage track. The track should be cleaned and lubricated occasionally for best performance. The track can be cleaned by spreading a coat of kerosene or light oil, such as clock oil, over the whole outside of the center conductor, using a pipe cleaner or a cloth.

The carriage is then slid back and forth several times to dislodge any dirt caught in the felt rings on the carriage; then the track should be wiped dry with a cloth. This procedure should be repeated until the wiping cloth does not pick up any dirt. A small amount of oil should be left on the track after the final cleaning.

The slot itself can be cleaned with a pipe cleaner.

6.3 CENTERING OF PROBE IN SLOT

If the probe shield strikes the edge of the slot, erratic performance will be observed. The shield centering can be checked by holding the line up to a light source and sighting from one end along the slot at the probe. The carriage should be moved along the line and the centering of the probe shield observed.

If the probe is not centered, it can be adjusted by loosening the line in its mounting and rotating it slightly. The line is locked in position by two Allen set screws, one located in each end bracket. These set screws are on the bottom side of the line and can be reached through holes in the center of the cross-strut at the bottom of each end bracket.

6.4 REMOVAL OF THE CENTER CONDUCTOR

The center conductor should not be removed unless absolutely necessary, as it is adjusted at the factory for the most uniform probe coupling. However, if it becomes necessary to remove the center conductor, it can be accomplished in the following manner:

First, loosen the set screws, locking the line to the brackets, as outlined in Paragraph 6.3. Then, slide the line a few inches in one direction until the coupling nut on the Type 874 Connector is available. Unscrew the coupling nut, being careful not to put a strain on the probe shield in the slot, and remove the connector. The center conductor can then be extracted from the line. The conductor can be replaced in a similar manner.

The center conductor in the line is straightened before assemble of the line, so the runout is less than 5 mils. In order to minimize the variation in probe coupling resulting from bends in the center conductor, the center conductor is rotated until the most uniform probe coupling is obtained. The center conductor can be rotated after the line is completely assembled by means of a small screw driver inserted in the hole in the center of the inner connector element on either end of the line.

The variation in probe coupling can be checked at an audio frequency using the method described in Paragraph 5.2. Checks should be made for several settings of the center conductor and the optimum chosen. It should always be possible to obtain a probe coupling variation of less than $\pm 2\text{-}1/2$ percent when the probe coupling is less than 30 percent.

Specifications

Characteristic Impedance: 50 ohms ± 1%.

Probe Travel: 50 centimeters; scale is calibrated in millimeters.

Frequency Range: 300 to 5000 megacycles. Operation at frequencies below 300 Mc is possible, if lengths of Type 874-L30 Air Line are added. Can also be used with some reduction in accuracy to 7000 Mc.

Dielectric: Air.

Accuracy: Constancy of Probe Penetration — ± 2-1/2% or better.

VSWR of Terminal Connectors: Less than 1.02 at 1000 Mc.
Less than 1.07 at 4000 Mc.

Crystal Rectifier: 1N21B-type silicon crystal.

Accessories Required: (Type 874-D20) Adjustable Stub for tuning the crystal rectifier; suitable detector and generator; one each Type 874-R20 and Type 874-R32 Patch Cords for generator and detector connections.

Other Useful Accessories: Type 874-WM 50-Ohm Termination, Type 874-WN and WN3 Short-Circuit Terminations, and Type 874-WO and WO3 Terminations. For the measurement of high standing-wave ratios (greater than 10), a Type 874-LV Micrometer Vernier is recommended. Adaptors to other standard coaxial connectors are available (see table on page 23).

Dimensions: 26 x 4-1/2 x 3-1/2 inches, over-all.

Net Weight: 8-1/2 pounds.

U.S. Patent Numbers: 2,125,816; 2,548,457.

Several copies of the appropriate Smith Charts are furnished with the Type 874-LB Slotted Line. Additional copies can be obtained from the General Radio Company at the following prices:

Quantity	Price
50	2.00
100	3.00
250	6.25
500	11.25
1000	20.00
2000	37.50

When ordering, please specify Impedance Coordinates (Form 756-Z), Admittance Coordinates (Form 756-Y), or Normalized Coordinates.